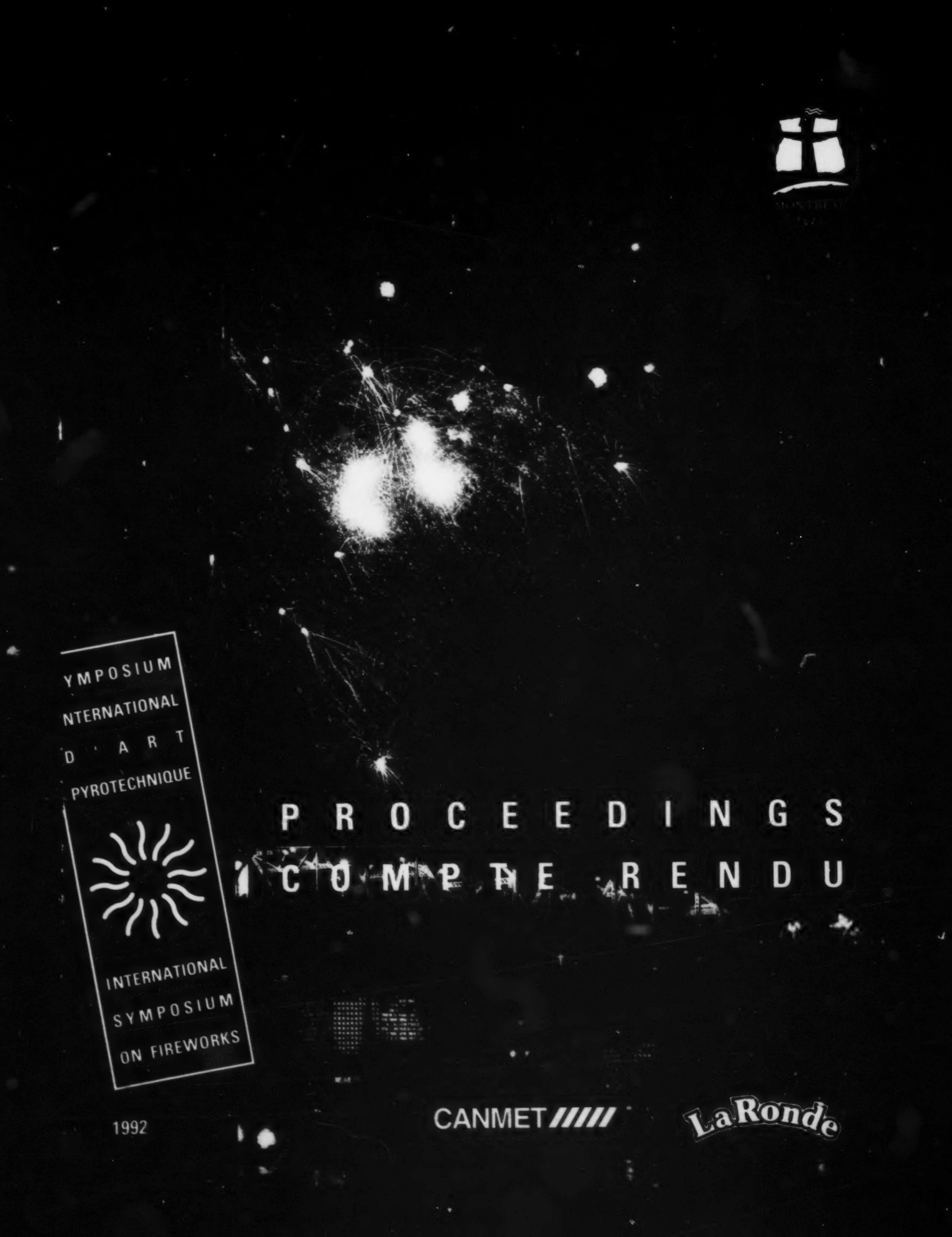

YMPOSIUM
NTERNATIONAL
D'ART
PYROTECHNIQUE

INTERNATIONAL
SYMPOSIUM
ON FIREWORKS

PROCEEDINGS
COMPTE RENDU

1992

CANMET

La Ronde

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PROCEEDINGS
OF THE FIRST
INTERNATIONAL SYMPOSIUM ON FIREWORKS

May 13-15, 1992

Montréal, Canada

386 pp

ACTES
DU PREMIER
SYMPOSIUM INTERNATIONAL D'ART PYROTECHNIQUE

Du 13 au 15 mai 1992

Montréal, Canada

92-04874/

PREFACE

This International Symposium on Fireworks is the first of its kind that is completely dedicated to the art, safety, research and regulation of fireworks and indoor pyrotechnics. Its objective is to bring together scientists, artists, manufacturers, and regulators that are actively engaged in these fields to present and discuss their most up-to-date findings.

To achieve a well balanced effort, review papers were invited in the areas of art, safety, research, and regulation. Thus, the proceedings are comprised of approximately 30 presentations by some of the most knowledgeable people in these areas. The papers have been reviewed by at least two experts in the field to ensure a professional document.

As program chairman, I would like to thank you, the speakers and session chairpersons, for your very positive response in accepting a degree of responsibility for the success of the first International Symposium on Fireworks.

I would also like to extend our appreciation to the American Pyrotechnics Association (APA) for offsetting part of the costs for the publication of the Proceedings.

Ettore Contestabile
Program Chairman

PRÉFACE

Le Symposium international d'art pyrotechnique est le premier du genre à être entièrement consacré à l'art, à la sécurité, à la recherche et à la réglementation des feux d'artifice et des procédés pyrotechniques d'intérieur. Il a pour objectif de réunir les principaux acteurs dans le domaine, scientifiques, artistes, fabricants et responsables de la réglementation, et de leur donner l'occasion de présenter leurs innovations et d'en discuter.

Pour donner une vue d'ensemble de tous les aspects de l'art pyrotechnique, des spécialistes oeuvrant dans les champs de l'art, de la sécurité, de la recherche et de la réglementation ont été invités à présenter des exposés. Les Actes du symposium comprennent ainsi une trentaine d'exposés rédigés par des auteurs très réputés dans leur discipline. Les documents ont été révisés par au moins deux spécialistes de la question traitée afin d'en assurer la qualité professionnelle.

À titre de président des conférences, je désire remercier tous les conférenciers et les présidents de session qui ont généreusement accepté de travailler à la réussite du Premier Symposium international d'art pyrotechnique.

Je desire exprimer notre reconnaissance envers l'Association Pyrothecnique Americaine (APA) pour absorber une portion des frais pour la publication des compte rendu.

Ettore Contestabile
Président des conférences

PROCEEDINGS
OF THE FIRST
INTERNATIONAL SYMPOSIUM ON FIREWORKS

May 13-15, 1992

Montréal, Canada

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ACTES
DU PREMIER SYMPOSIUM INTERNATIONAL D'ART PYROTECHNIQUE

Du 13 au 15 mai 1992
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Parrains

Centre canadien de la technologie des minéraux
et de l'énergie (CANMET)
Ottawa, Canada

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"LA PYROTECHNIE AU CANADA"

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RÉSUMÉ

Le 13 mars 1973 Le Conseil Privé, apporte une modification aux Règlements sur les explosifs, établis par le décret C.P. 1973-573. Toutes pièces pyrotechniques rentrent dans la classe 7.

L'age requis pour les pièces pyrotechniques, et les fabriquants et distributeurs de piéces pyrotechniques au Canada.

Le Manuel de l'Artificier et ses généralitées. Le dossier Canadien en se qui regarde la sécurité sur les pièces pyrotechniques.

ABSTRACT

In 1973 the Privy Council of Canada established amendments to the Explosives Act and Regulations by a decree. From that date all pyrotechnics were to be classed as Class 7.

Age required to purchase, the manufacturers and distributors of pyrotechnics in Canada.

The Fireworks Manual and its generalities. The Canadian record on safety in pyrotechnics.

CLASSIFICATION DES PIÈCES PYROTECHNIQUES

Le 13 mars 1973 Le Conseil Privé, apporte une modification aux Règlements sur les explosifs, établis par le décret C.P. 1973-573. Toutes pièces pyrotechniques rentrent dans la classe 7.

Classe 7.1	Classe 7 division 1 comprend: les compositions pyrotechniques
Classe 7.2.1	Classe 7 division 2 subdivision 1 comprend: pièces pyrotechniques comportant un risque restreint pour divertissement: petites chandelles romaines, volcans, étinceleurs, soleils tournants, fontaines etc. désigné: articles de magasin.
Classe 7.2.2	Classe 7 division 2 subdivision 2 comprend: pièces pyrotechniques comportant un risque élevé pour divertissement: obus, fusées, bombardos, girondolas, grands soleils, bouquets, barrages etc. désigné: pièces pyrotechniques pour les grands feux d'artifice.
Classe 7.2.3	Classe 7 division 2 subdivision 3 comprend: moteurs - fusées miniatures (dispositif de propulsion de jouets).
Classe 7.2.4	Classe 7 division 2 subdivision 4 comprend: pièces utilitaires comportant un risque restreint torches de signalisation routière et ferroviaire, et autres petits signaux de détresse (pour petits bateaux, chasseurs etc.)
Classe 7.2.5	Classe 7 division 2 subdivision 5 comprend pièces utilitaires comportant un risque élevé: les gros signaux de détresse, signaux sonores, fumigènes, pétards ferroviaire, fusées de détresse, fusées lance-amarre, pièces théatrales, effets scémiques, dispositifs contrôle de la faune etc.

Caps à Pistolet	le seul explosif permit pour enfants (en bas de 18 ans)- (avec les moteurs fusées 12, ans)
Classe 7.2.1	18 ans
Classe 7.2.2	détenteur d'une carte d'Artificier - Surveil-lant et avoir l'autorisation municipale (remplir une demande d'achat). (i) Voir la copie de Demande d'Achat sur le l'écran.
Classe 7.2.3	12 ans avec la supervision d'un adulte.

Classe 7.2.4	aucune restriction
Classe 7.2.5	la vente de pièces de cette classe sont restreinte aux personnes qui exercent l'occupation pour laquelle ces pièces pyrotechniques ont été conçues et autorisées.

Pétards sont dans la classe 7.2.2, Obtenir l'approbation de l'Inspecteur en Chef des explosifs, et l'autorisation municipale (Directeur des incendies).

Toutes pièces pyrotechniques fabriquées au Canada ou importées, doivent être autorisées par la Division des explosifs. Chaque année, au printemps, vous pouvez vous procurer la liste des explosifs (pièces pyrotechniques) autorisés; qui est un supplément de la Gazette du Canada - Partie I.

FABRIQUE DE PIÈCES PYROTECHNIQUES AU CANADA:

Feux d'àrtifice Hands

DISTRIBUTEUR DE PIÈCES PYROTECHNIQUES AU CANADA:

Ampleman Pyrotechnie
Feux d'artifice B.E.M.
Fiatlux
International Fireworks

MANUEL DE L'ARTIFICIER

Le Manuel de l'Artificier comprend le cours, pour les déploiements pyrotechniques, soit la classe 7.2.2. Ce manuel a neuf sections.

section 1 - Généralités

section 2 - Description des pièces pyrotechniques

section 3 - Régles de sécurité pour les feux d'artifice

section 4 - Pièces pyrotechniques de haute-portée

section 5 - Pièces pyrotechniques de basse-portée

section 6 - Pièces pyrotechniques au niveau du sol section 7 - Enlèvement des pièces ratées et rapport sur les défectuosités ou accidents

section 8 - Entreposage et transport

section 9 - Pétards

BUT: Ce guide a été préparé à l'intention des personnes responsables et compétentes afin de minimiser les risques d'incendies et de blessures. Aussi, ce guide est très utile pour ceux qui sont chargés de l'application des lois provinciales ou des reglements municipaux.

Au Canada toute demande d'achat pour les déploiements (classe 7.2.2) doivent être approuvé et signé par l'autorité municipale (Directeur des incendies).

PIÈCES PYROTECHNIQUES DE HAUTE-PORTÉE

1) fusées - volantes

2) bombes (obus) (155 mm - 6" maximum) etc.

Pour les obus de plus gros format, une permission spéciale doit-être obtenue de l'Inspecteur en chef des explosifs. Cette permission est accordée seulement aux articiciers surveillants avec de l'expérience. Pour les compagnies (experts) les obus sont permises j'usqu'à 305 mm (12"). Toute les pièces de haute porteé doivent être disposées au minimum de 100 m des spectateurs.

PIÈCES PYROTECHNIQUES DE BASSE-PORTÉE

Bombardos, Girondolas, barrages, tourbillons, soucoupes volantes, chandelles-romaines (45mm et 60 mm) etc. Doivent être disposées au minimum de 45 m des spectateurs.

PIÈCES PYROTECHNIQUES AU NIVEAU DU SOL

Chandelles romaines, batteries, fontaines, gerbes, mines, roues, bengales et illuminations, pièces montées, chutes, et pigeons etc. Doivent être disposées au minimum de 35 m des spectateurs. Il faut se rappeler que toutes ces pièces pyrotechniques doivent être sur la liste des explosifs autorisés au Canada.

(ii) Dimensions des terrains recommandés. Voir l'écran.

(iii) Dimensions minimales recommendées pour les sites de lancement en ce qui regarde chaque grosseur des bombes, jusqu'a 305 mm (12"). Voir l'écran.

DIVISION DES EXPLOSIFS

GROSSEUR DES BOMBES		DIMENSIONS MINIMALES RECOMMANDÉES	
(MM)	(PO)	(MÉTRES)	(PIEDS)
50	2	200 x 200	600 x 600
76	3	200 x 200	600 x 600
102	4	200 x 200	600 x 600
127	5	200 x 200	600 x 600
155	6	200 x 300	600 x 900
205	8	230 x 300	700 x 900
255	10	265 x 300	800 x 900
305	12	335 x 335	1000 x 1000

RÈGLES DE SÉCURITÈ

1) La sécurité est d'une importance primordial lors d'un déploiement pyrotechnique.

2) Assurance - responsabilité

3) Inspection des pièces

4) Lire les instructions du fabriquant

5) Artificier - Surveillant et adjoints
    A) 18 ans - pour l'artificier
    B) fonctions des adjoints (2)
    C) possession de toute leur faculté
    D) avoir vêtements ignifuges
    E) préposés au contrôle des spectateurs doivent êtres exemptés de toute autre responsabilité
    F) contrôle de la foule
    G) protection contre les incendies.

APPRÊS LE FEU

1) Inspection du terrain: 1/2 hr. après le déploiement le terrain doit-être fouillé minitieusement, pour les pièces pyrotechniques oubliés, ratées, ou des parties inexplosées et retombées au sol. Le lendemain à l'aube, une autre inspection est requise.

2) Enlèvement des pièces ratées: Ces pièces doivent être détruites avec precaution dans une sablière, ou retournées au fabriquant pour inspection.

   Certains détachements de police, peuvent se charger de la destruction de ces pièces.

3) Nettoyage du terrain: remettre le terrain en bonne condition.

4) Rapport des défectuositées: un rapport doit être soumi à l'Inspecteur en chef des explosifs.

   Ceci assurera la qualité des pièces pyrotechnique sur le marché.

5) Rapport d'accidents: tout accident doit être soumi à l'Inspecteur en chef des explosifs.

Entreposage - lorsque le poid brut ne dépasse pas 125 kg, les pièces peuvent être conservées dans un entrepôt, garage au bâtiment similaire. Environ 15 m de tout endroit publique. Excédant 125 kg, les pièces doivent être remisees dans un dépôt licencié.

Transport - Les pièces pyrotechniques de la classe 7.2.2 sont classifiés comme suit:

Pièces pyrotechniques ONU 0335, code 1.3 G
L'expéditeur doit veiller que ces pièces soient emballées, étiquetées comme il se doit et y joindre la documentation pertinente avant de les livrer au transporteur. Les affiches (250 mm x 250 mm) doivent être posées sur les quatres côtés du véhicule. Ces affiches oranges indiqueront: "Explosif 1.3G"

Pour les bombes (obus) de: 205 mm (8"), 255 mm (10") et 305 mm (12") les étiquettes oranges indiqueront "Explosif 1.2G".

DÉPLOIEMENTS PYROTECHNIQUES AU CANADA

FEUX SPÉCIAUX avec autorisation spéciale de l'Inspecteur en chef des explosifs.

1) Concours internationale d'Art pyrotechnique de Montréal

2) Symposium des feux à Toronto (Benson & Hedges)

3) Symposium des feux à Vancouver (Benson & Hedges)

Lors de la "Fête du Canada" chaque ville du pays à son déploiement pyrotechnique avec un feu majeur sur la Colline à Ottawa.

Il en est de même pour villages et villes au Québec lors de la Saint-Jean Baptiste.

Dans l'ouest du Canada, le soir de l'Halloween, toutes les villes ont un déploiement pyrotechnique.

La "Fête de la Reine" à toujours été un grand jour pour la pyrotechnie au Canada, et si vous avez l'opportunité d'être présent dans une grande ville en Ontario, lors de cette journée, vous serez témoin de très gros déploiement.

En plus, dans les territoires du Nord et le Yukon, la pyrotechnie est très populaire la veille du Jour de l'an. Que c'est beau, commencer l'année avec un feu d'artifice.

Dans les Maritimes, "Natal-Day" apporte à la ville de Halifax un gros déploiement, de même à St-Jean, Terreneuve. Aussi, plusieurs déploiements dans autres villes des Maritimes lors du "Civic Day".

Comme vous le savez, mes amis, pour chaque événement spécial qui se produit au Canada, dans la majorité des cas, c'est toujours accompagné d'un déploiement pyrotechnique.

Les Carnavals
Expositions - régionales - locales
Bal de Neige
Festivals
Course bateaux - automobiles
Inauguration de Centres, sportifs - édifices publiques etc.

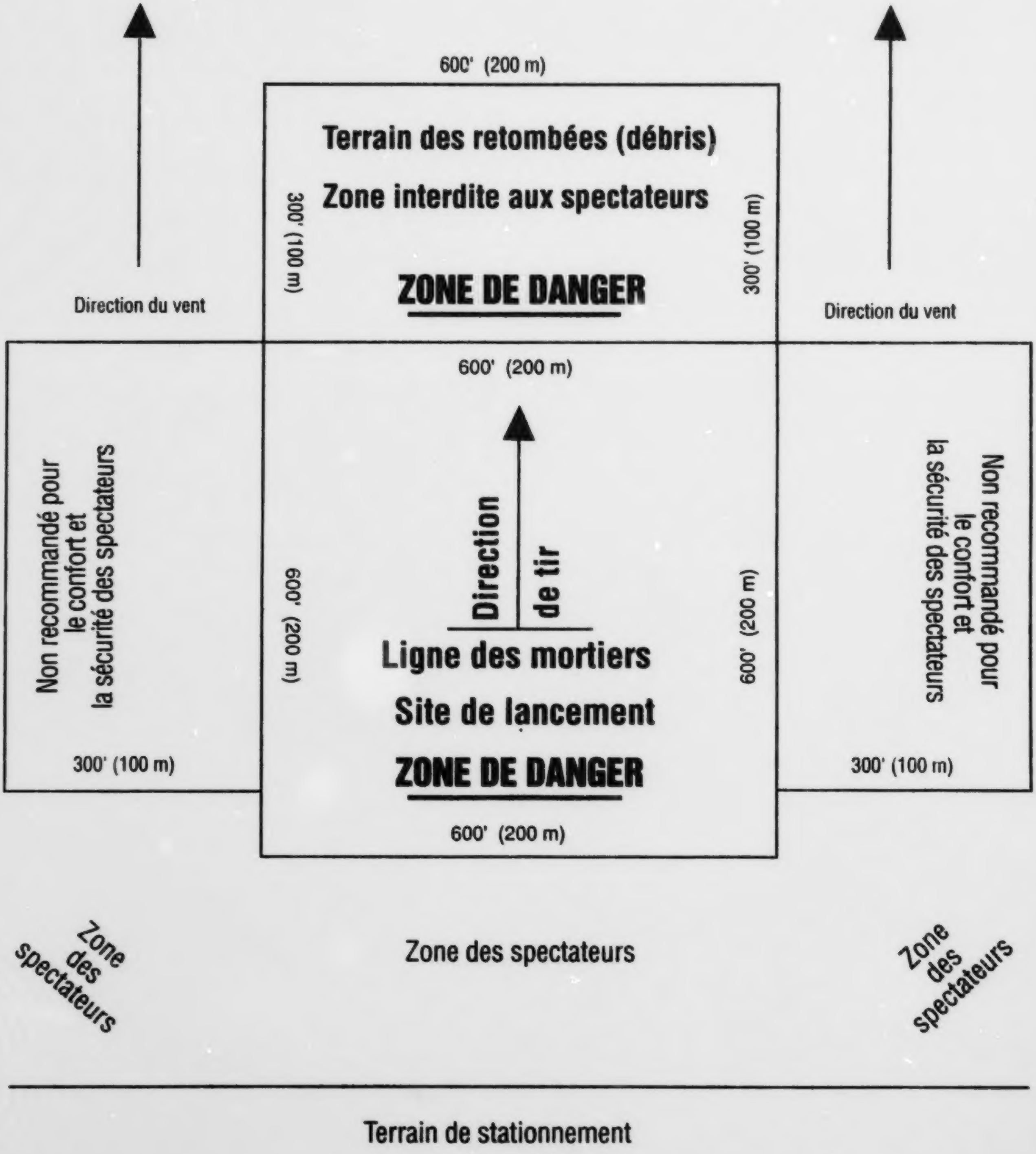
Ayant parcouru le Canada entier par mes fonctions, il m'est agréable de vous dire "La pyrotechnie est très populaire au Canada." En cette année 1992, ca fait 20 ans, que le Gouvernement Canadien à amendé la Loi sur les explosifs en ce qui regarde les pièces pyrotechniques.

J'ai le plaisir de vous mentionné, qu'aucun accident mortel ou grave n'a eu lieu, lors de ces déploiements pyrotechniques de la classe 7.2.2.
La Division des explosifs - est très fier des:

Compagnies
Artificiers - Surveillants
Autoritées - Municipales
(Departement des incendies)

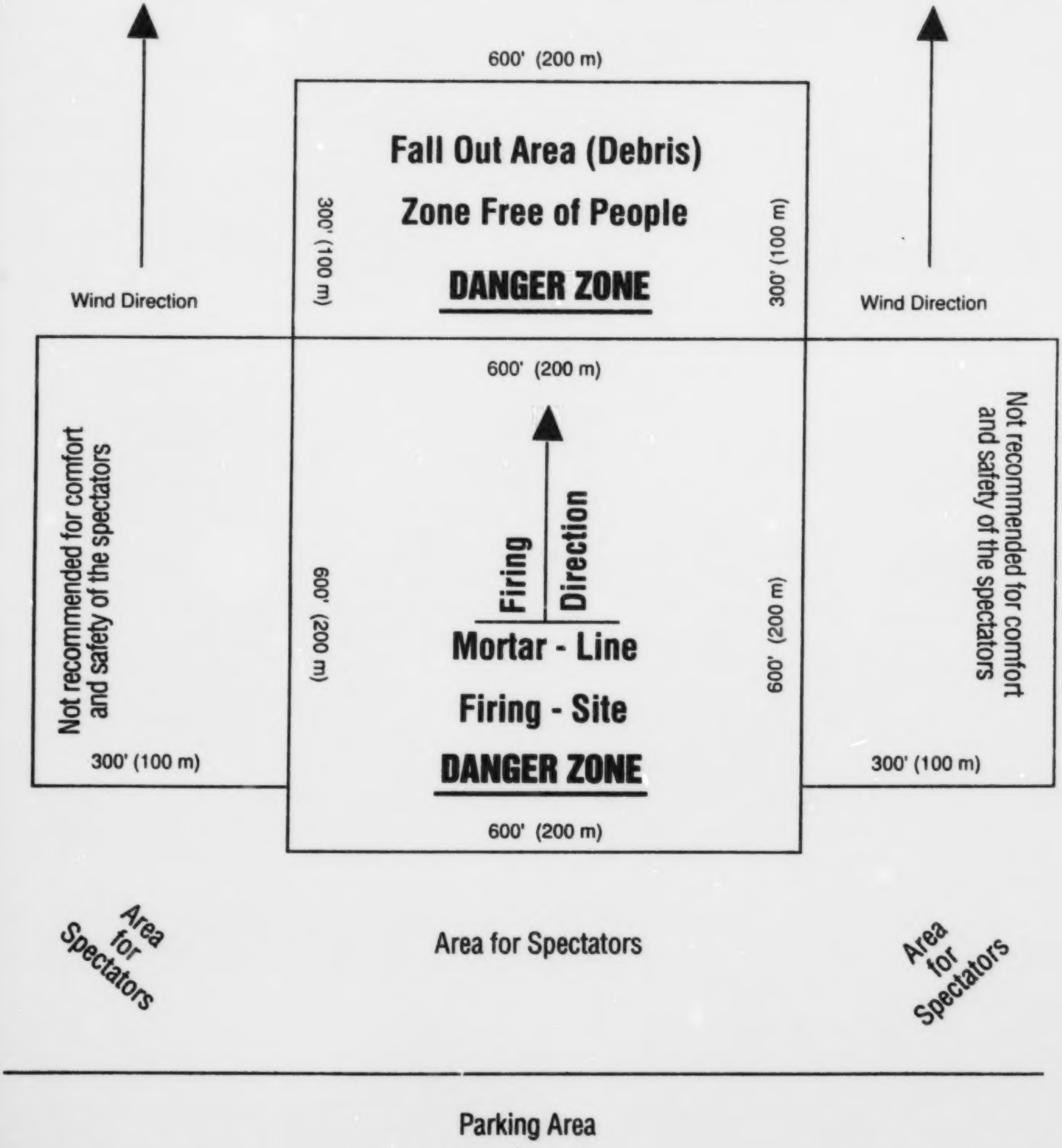
Dimensions minimales recommandées pour un feu d'artifice

pour grosseur des bombes 155 mm (6") maximum


600' (200 m)
Terrain des retombées (débris)
Zone interdite aux spectateurs
300' (100 m)
300' (100 m)
ZONE DE DANGER
Direction du vent
Direction du vent
600' (200 m)
Non recommandé pour le confort et la sécurité des spectateurs
Non recommandé pour le confort et la sécurité des spectateurs
Direction de tir
600' (200 m)
600' (200 m)
Ligne des mortiers
Site de lancement
ZONE DE DANGER
300' (100 m)
300' (100 m)
600' (200 m)
Zone des spectateurs
Zone des spectateurs
Zone des spectateurs
Terrain de stationnement

Recommended Minimum Dimensions of Field for a Fireworks Display

for shell size 155 mm (6") maximum


600' (200 m)
Wind Direction
Wind Direction
Fall Out Area (Debris)
Zone Free of People
DANGER ZONE
300' (100 m)
300' (100 m)
600' (200 m)
Not recommended for comfort and safety of the spectators
Not recommended for comfort and safety of the spectators
Firing Direction
600' (200 m)
600' (200 m)
Mortar - Line
Firing - Site
DANGER ZONE
300' (100 m)
300' (100 m)
600' (200 m)
Area for Spectators
Area for Spectators
Area for Spectators
Parking Area

PROTECTED
PROTEGÉ

Energy, Mines and Resources Canada
Énergie, Mines et Ressources Canada

APPLICATION TO PURCHASE - DEMANDED'ACHAT

CLASS 7.2 .2. HIGH HAZARD FIREWORKS FOR RECREATION
CLASSE 7.2.2. PIÈCES PYROTECHNIQUES COMPORTANT UN RISQUE ÉLEVÉ , POUR DIVERTISSEMENT

1- Applicant must be the person supervising the fireworks
L'acquéreur doit étre celui qui dirige la mise à piéces pyrotechniques

2- Submit application to supplier with your order
Veuillez soumettre la demande d'achat au fournisser avec votre commande

3 - Please print
Veuillez compléter en lettres moulées.

Name of Applicant- Nom de L'acquéreur	Age- Agé
Mailing Address - Addresse	
Postal Code - Code Postal	Telephone - Téléphone Area Code/ L'indicatif Régional ______________________

I hereby make application an application to purchase 7.2.2. fireworks
Par la présente, je frais une demande pour l'achat de piéces pyrotechniques de la classe 7.2.2.
au nom de

Myself ☐ or :
Moi-même ou :

Sponsoring Organization - Nom du Commanditaire		
Address-Addresse		
Location of Display / Lieu de la Démonstration	Date	Time- Heure

I CERIFY THAT I HAVE COMPLETED A COURSE FOR FIREWORKS SUPERVISORS, HAVE READ , UNDERSTAND AND WILL BE GUIDED BY THE PRINCIPLES AND SAFETY RULES OF THE FIREWORKS MANUAL AND THE THE SPECIFIC INSTRUCTIONS OF THE MANUFACTURER GOVERNING A PARTICULAR FIREWORK.

JE CERTIFIE AVOIR COMPLÉTÉ UN COURS D'ARTIFICIER SURVEILLANT, AVOIR LU,COMPRIS ET M'ENGAGE À RESPECTER LES PRINCIPES ET LES RÉGLES DE SÉCURITÉ DU MANUEL DE L'ARTIFICIER ET LES INSTRUCTIONS DU FABRICANT SE RAPPORTANT À CHAQUE PIÉCE PYROTECHNIQUE.

Fireworks Supervisor Card No.- Numéro de Carte	Expiry Date - Date D'expiration
Date	Signature of Applicant / Signature de L'acquéreur

PERMISSION OF LOCAL AUTHORITY - PARTIE RÉSERVÉE À L'AUTHORITÉ LOCALE

NOTE; TO BE COMPLETED BY THE LOCAL AUTHORITY HAVING JURISDICTION OVER FIREWORKS DISPLAYS (FIRE CHIEF)
À ÉTRE COMPLETÉE PAR L'AUTORITÉ LOCALE AYANT JURIDICTION SUR LES DEMONSTRATION DE PIÉCES PYROTECHNIQUES (DIRECTEUR DES INCENDIES)

The applicant has complied with local requirements and has permission to hold a fireworks display at the location and time mentioned above.
Les exigences locales ayant été remplies, l'acquéreur a l'autorisation de tenir un déploiement de feux d'artifice au lieu et à l'heure susmentionnes.

Signature of Local Authority - Signature de L'autorité Locale	Name - Nom
Title - Titre	
City Town Municipality - Ville , Village, Municipalite	

EMR/MET - 540-60522
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EMR 931(90-07)

THE EVALUATION OF LOW HAZARD FIREWORKS
("Family Fireworks")

Richard A. Bowes
Canadian Explosives Research Laboratory
CANMET, 555 Booth Street
Ottawa, Ontario, CANADA, K1A 0G1

ABSTRACT

The Canadian Explosives Research Laboratory (CERL) has been evaluating fireworks for 73 years. CERL, with the Explosives Division, has drafted standards on which the acceptance of fireworks will depend in the future. This, together with the occurrence of accidents, prompted a detailed study of fireworks already on the market. The study revealed a lack of quality control in some fireworks and showed that many fireworks did not meet the standards. There are also dilemmas in respect of the Transport of Dangerous Goods classification of low hazard fireworks and the allowable limits of report composition in fireworks.

BACKGROUND

Energy, Mines and Resources Canada, formerly the Department of Mines, has been testing explosives for at least 73 years. The Explosives Division Annual Report for 1919 describes the existence of a laboratory on the corner of Kent and Victoria Streets in Ottawa. This laboratory was set up by an Order-in-Council (No. 482) to analyze and test explosives and to determine their suitability for classification as "authorized explosives" under, the then newly proclaimed, Explosives Act.

In the 1900's, parties with interests in the manufacture of explosives, felt the need for control to be placed on new explosives entering the market and for regulation of the conditions, from a safety perspective, under which they could be manufactured and stored. The frequency with which accidents were happening, especially in mining and railway construction emphasized this need and resulted in the Department of Mines in co-operation with the manufacturers, examining the question of regulation. This effort led to the proclamation of the Explosives Act after the First World War in 1919. This Act was based on the United Kingdom's Explosives Act of 1875. It required the classification of explosives under a system of 7 classes that had been found adequate for regulation in the United Kingdom for 30 years.

The system of classification is still used in the present Explosives Act, although, it will be substantially revised in the near future. Under the system, all manufactured fireworks were placed in Division 2 of Class 7 (Class 7 explosives are fireworks.) Fireworks that were intended for sale through retail outlets were later placed in a sub-division (Sub-division 7.2.1-low hazard fireworks).

Over the years the examination of low hazard fireworks has been a major function of the laboratory and in some years during the thirties and fifties accounted for as much as 90% of the number of samples that the laboratory examined. Low hazard fireworks have also always been problematic and early annual reports refer to failures because of erratic fuse times and ejection of smouldering material. Chinese firecrackers were restricted to those up to 10 cm long and only those that contained black powder. American salutes were banned at an early stage after reports of a US accident involving salutes that killed 10 and injured 27 persons.

The laboratory was relocated to Uplands in 1953 and relocated to the Bells Corners Complex in the 1960's when it became part of Energy, Mines and Resources' CANMET. Today, under the name "Canadian Explosives Research Laboratory," it continues to analyze and test explosives including fireworks to ensure their safety. Low hazard fireworks continue to represent a major concern and account for 30-50% of the number of samples that are examined for the Explosives Division.

STANDARDS

CERL and the Explosives Division have drafted a standard for the construction, labelling and performance of low hazard fireworks. The latest version was released in November 1990. The standards set out general requirements and those specific to each of 13 types of firework. The standards also list forbidden types of fireworks.

The general requirements deal with the Transport of Dangerous Goods classification (all Division 1.4, Compatibility Group G or S), transport packaging (must follow Transportation of Dangerous Goods Act), sampling requirements, robustness and variability in burn times. Fireworks must also be thermally stable (UN Series 4(a) test) and must be capable of passing a 12 m drop test (UN Series 4(b) test) in their packaged form. There are prohibitions on articles containing certain compositions.

The specific types of fireworks are:

1. Barrage/battery
2. Bouquets
3. Flare
4. Fountain
5. Mines
6. Pull-string crackers
7. Replica
8. Roman Candles
9. Snake
10. Sparkler
11. Toy Pistol Caps
12. Wheel
13. Others

A large number of fireworks are defined by the types - fountain, mine and Roman Candle. The definitions, which may differ from other national definitions, of these three types are:

1. "A fountain is a rolled paper or cardboard tube or cone containing composition which, when ignited produces a jet or shower of sparks from an orifice".
2. "A mine is a closed box or cylindrical tube which when ignited, produces a series of effects such as a shower of sparks, a flare, or burning stars and culminates with a loud report as a final effect".
3. "A Roman candle consists of a cardboard or a cylindrically wound tube containing pyrotechnic compositions which, when ignited shoots flaming balls of stars into the air at regular intervals".

Defining types is problematic because of the efforts of manufacturers to produce a variety of novel products. The type names are based on historical types of fireworks and in some cases are based on trade names. There have been suggestions that the types should be identified by code rather name. Table 1 summarizes some of the requirements for specific types of fireworks given in the Class 7.2.1 standards.

ACCIDENTS

In 1989 there were two serious accidents involving "7.2.1" fireworks. Both involved some measure of misuse of the fireworks by the affected persons but laboratory examination of samples of the fireworks raised serious questions about their quality and construction.

The first accident involved a small Roman candle which had the tendency to explode after the ejection of 2 to 3 stars. The user had placed the Roman candle in a metal casing and the ensuing explosion caused metal to penetrate the user's chest resulting in his death. X-ray examination of these Roman candles showed that some of them had up to 3 times more lift charge beneath each star than other Roman candles from the same production batches. The stars were frequently broken and often not in the correct order. The most likely cause of the explosive behaviour was eventually concluded to be a problem in the construction of the cylindrically wound tube; the inner layer of cardboard was partially detached and, was curling into the composition providing a channel for premature ignition of the lift charges. This, combined with the overloading, caused the candles to explode.

The second accident involved a mine which contained reports. These reports functioned simultaneously in the tube after the main fuse had burnt through instead of being ejected. This resulted in the user's hand being severely injured. There were reports of similar malfunctions but without injury. In this case laboratory examination showed that samples contained report charges 4 times larger than authorized. The report charges were handmade and there was considerable variation from one to the other. The cause of the premature functioning of the reports was probably caused by leakage of report composition from the tied closures on the reports.

FIREWORKS MONITORING

The problems resulted in a program aimed at re-evaluating all the fireworks on the Canadian market to ensure that they met the original manufacturer's declarations and that they were safe. This also provided an opportunity for all the authorized fireworks to be compared against the standards.

All fireworks examined under this project were subjected to a comprehensive evaluation. They were physically examined and their dimensions, integrity and labelling noted. They were radiographed to reveal the internal construction of the fireworks and facilitate their selection for disassembly for charge weight determination and analysis of their compositions, and selection for function.

The compositions were analyzed chemically to confirm the declarations of the manufacturers and analyzed for their thermochemical properties and stability by differential scanning calorimetry.

A minimum of 6 articles were functioned and the fuse times, function times, height and radius of effect, noise level and fire hazard were evaluated. The functions were recorded on video tape. The results of the program are summarized in Table 2.

It was also found that less than 50% of the fireworks on the market conformed to the standards. This will result in a change in the standards where appropriate and also possibly the elimination of some products from the market.

TRANSPORT OF DANGEROUS GOODS CLASSIFICATION

The UN Transport of Dangerous Goods Division 1.4 consists of substances and articles that do not present a significant risk. Substances and articles in this division present a low risk on ignition or initiation during transport. The effects remain largely within the package and should not cause the projection of large fragments or project fragments to a large distance. Exposure to external fire should not cause a near instantaneous explosion of the total contents of the package.

According to the UN Transport of Dangerous Goods classification scheme, Test Series 6 determines the division to which an article or substance is assigned. In September 1990, packages containing 5, 8, 10 and 12 ball Roman candles were subjected to a Series 6(c) test as defined in the Recommendations on the Transport of Dangerous Goods - Tests and Criteria document.

The result was that the fibreboard packagings burned through very rapidly and most of the Roman candles fuses were ignited rapidly. Most of the candles began functioning within 6 s of the degradation of the packagings. The candles were in a horizontal orientation in the packagings as they would be in their normal transport or storage situation. The candles functioned normally producing a hail of ignited stars. Some of the stars impacted the witness panels but did not produce any significant damage. Some of the stars travelled up to 54 m from the bonfire where they ignited the natural vegetation. The peak radiometer reading at 5 m from the stack was 0.014 kW/m^2. The scaled peak reading at 15 m was 0.0016 kW/m^2 and 0.0020 kW/m^2/100 kg. These figures are insignificant with regards to the Division 1.3 thermal flux limits. No signal above background was detected at the radiometer at 15 m.

In the Series 6(c) test, one of the criteria for acceptance into Division 1.4 is the emanation of "fiery projections" from the product to more than 15 m from the edge of the stack. Burning stars would be considered as "fiery projections".

This test was conducted on a product that ejects 5 g stars. There are many mines and pre-loaded mortars presently considered to be "7.2.1" that contain 50 g comets or 75 g shells that project vertically to 30 m. They would probably also be accepted into Division 1.3 in a Series 6(c) test.

While there may be some debate as to how accurately it defines the risk presented by them, the results of this test indicate that many items that have been considered as Division 1.4 are actually Division 1.3. No re-classification is considered at present, but the consequences of re-classification would be serious for manufacturers and distributors. The consequences would also be serious where the Transport of Dangerous Goods classification has been used for control not related to transport, such as use. It is possible that the term "fiery projection" may need to be defined in the Tests and Criteria document.

THE DILEMMA OF BLACK POWDER VERSUS "FLASH" COMPOSITION

Chinese firecrackers not considered to be low hazard fireworks in Canada. Black powder firecrackers are permitted are for use in controlled displays but so called flash crackers are not permitted per se. Increasingly, Chinese firecrackers are being used as internal components of low hazard fireworks and frequently these are "flash" crackers. These create an awkward situation where legally distributed fireworks contain components that by themselves are considered to be illegal. The main concern is safety.

The original concept of a firecracker contained 80 mg of black powder. In most cases, the powder is a "flash" composition which can be many times more powerful than black powder. This is compounded by the existence of reports shells that contain up to 10 g of "flash" composition.

Krone and Treumann have studied "flash" compositions and report heats of explosion of 10 different "flash" compositions as ranging from 174 kJ/kg to 9300 kJ/kg, and lead block expansions from 0 mL/10 g to 374 mL/10 g. The heat of explosion for black powder is reported as 764 kJ/kg in Meyer. It is clear that not only is there a tremendous range in the properties of "flash" composition but also that some "flash" compositions are many times more energetic than black powder.

CERL will conduct tests on the types of reports used in fireworks to compare the effects of "flash" composition with black powder and establish a reasonable size for reports.

CONCLUSIONS

The examinations have highlighted quality problems and difficulties in applying the standards. There are still some issues to be resolved in terms of Transport of Dangerous Goods classification and report components but it is intended that the outcome will be that fireworks on the market will be safer and more reliable. This will not only be of benefit to the users of fireworks but also to the industry at large which faces the prospect of bans and increased regulation with every serious accident.

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Table 1 – Summary of Specific Requirements of Class 7.2.1 Standards

	Max. charge weight g	Max. length mm	Max. diamet mm	Base	Fuse time s	Max. height m	Max. noise level at 5 m, dB(A)	Comments
1. Barrage/battery	*	*	*	–	3–6	*	140	
2. Bouquets	*	*	*	–	3–6	*	140	
3. Flare	100	254	32		3–6	0.15	–	not greater that 3 min
4. Fountain, cylindrical conical	75 50	250 250	20 –	> 1/3 length	3–6 3–6	4 4	140 140	
5. Mines	40	305	65	–	3–6	–	140	no debris more than 5 m from article
6. Pull–string crackers	0.015	–	–		–	–	140 at .45 m	function without sparks or smoldering material
7. Replica	*	*	*	*	3–6	*	140	no burning of case after 30 s after copmpletion of function
8. Roman candles, < 8 balls 8 – 13 balls	40 25	150 150	14 inner 10 inner	bury bury	3–6 3–6	15 15	140 140	min. height of stars – 1 m min. height of stars – 1 m
9. Snake	5	–	–	–	–	–	–	must not contain salts of mercury, lead or other poisinous subetanc
10. Sparkler	20	750	3.4	–	–	–	–	min. length 150 mm, comp. coating max. 400 mm, min. diameter 0.88 mm, newspaper test, droop test
11. Toy pistol caps, ring/strip roll	6.5 / 1000 amorces 5.0 / 1000 amorces	– –	– –	– –	– –	– –	153 at .45 m 153 at .45 m	max 1000 amorces/package, max. charge density 0.04 $g \cdot cm^{-3}$, no amorce to amorce communication, leaching of chlorate into paper not permitted, failures < 5%, see standard for calc. of noise level based of 50 deteriminations
12. Wheel	60	200 driver tube	15 driver tube	–	3–6		140	must function for 5 s to 120 s, no sparks beyond 5 m
13. Other	–	–	–	–	–	–	140	

Notes: 1. * means that this type is a combination and the limitations for each type apply.
2. This table does not replace the the standards document. Consult the document for the full detail.

Table 2 – Summary of Fireworks Examination Findings

	Numbers of Fireworks Examined	Total Failures %	Failures on Charge Wt. and Dimensions %
1. Combinations	17	65	24
2. Forbidden	1	100	–
3. Hybrids	4	100	100
4. Fountain	19	53	42
5. Mines	34	34	14
6. Roman candles	14	71	57
7. Sparkler	9	33	33
8. Toy pistol caps	8	38	13
9. Wheel	5	20	–
10. Other	11	27	–

CRIMINAL ACTIVITIES USING FIREWORKS AND PYROTECHNICS

FEU D'ARTIFICE ET PYROTECHNIQUE UTILISÉS DANS DES ACTIVITIÉES CRIMINELLES

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Statistics concerning the past five years with slides showing different incidents and accidents involving illegal/unauthorized use and modification of pyrotechnic devices for the purpose of constructing improvised explosive devices.

Statistiques des cinq dernières années avec diapositives montrant différents incidents et accidents impliquant l'utilisation illégale ou non-autorisé et de la modification de pièces pyrotechniques dans le but de construire des engins de frabrication artisanale.

I am very pleased to represent the RCMP and the CBDC.

In Canada one-third of all incidents fall in the low explosives category. All incidents are broken down into the following categories:

BOMBINGS; those are the ones when an improvised explosive device functioned as intended;

ATTEMPTED BOMBINGS; those are the ones that did not function as intended or were partial bombs;

RECOVERIES OF IEDs; those are devices that we seized before they could be used;

HOAX DEVICES; are those devices that were made to look real but could not function because they do not contain an explosive or an incendiary component;

SAFE ATTACKS are those devices that are meant to break down safes or night deposit boxes mainly of financial institutions; and

ACCIDENTAL EXPLOSIONS; involve individuals injured while engaged in the process of making an improvised explosive device or in setting up legal explosions.

The statistics shown here represent the different incidents as reported to the CBDC. You must understand that statistics are only as good as what is being reported by the different police forces in Canada. This presentation is concentrating on incidents involving pyrotechnics and fireworks. This is a very short overview of the problems encountered with explosives used in an unauthorized manner and those used with criminal intent. The vast majority of bombings using pipe bombs come from black powder.

What is meant here is that the explosive contained in pipe bombs is black powder in nature. For the purpose of this presentation, black powder includes the explosive powder taken from shotgun shells, pyrotechnics or fireworks and it can be photoflash, smokeless, double base or home-made powder. All of these previously mentioned categories have been given a general heading of black powder for today since time does not permit us to a have a complete breakdown of each incidents by type of filler.

Looking at this table (Table 1), under sub-total, we had an increase of 35 incidents in 1991 which is approximately 16% over 1990; and once files are completed the trend should give us a 4% increase in devices that use pyrotechnics and fireworks. Also we expect to pass the 400 mark in the number of devices which is double the quantity of devices in 1989.

One point of importance to note is that in the past some devices that contained an item which was a pyrotechnic composition but didn't have all the components to be an explosive and/or incendiary device was put in the hoax device category. Since 1991 all devices that contained items like sparklers and railway fuse etc. have been considered to be incendiary in nature and not hoax devices. We have had a device that incorporated a railway fusee with a power source but the device did not function simply because it did not have sufficient power to ignite the railway fusee. Therefore from now on a hoax device will have no components that can be considered incendiary or explosive in nature.

From 1987 to 1990 in the hoax category there was only one incident in which firecrackers were used and it was a prank; all the other hoax devices utilized railway fusees to simulate dynamite sticks and all were used in extortion/robbery of a financial institution.

In the accidental explosion category we find that most are due to people who try to manufacture copper pipe bombs using match heads and, unfortunately, it is among teenagers that there are more accidents. The consequences have varied from death to loss of a whole hand or fingers or eyesight. The most common construction method is to acquire a piece of copper pipe, approximately 1/2 in. to 3/4 in. in diameter and of various lengths, to crimp one end, fill the pipe with match heads and crimp the other end using a hammer or a vice grip. When confined, match heads can have a devastating effect; one such pipe bomb made in 1991 contained 6000 match heads. Once made, these pipe bombs are unstable since they are very sensitive to friction or shock.

The rest of this presentation consists of a 1 minute and 20 second video of a test carried out by police explosives technicians to find out how a Canadian boy was killed when he experimented with a Roman candle. He had inserted the firework into a bicycle pump and then lit it while holding the pump in his hand. This video will followed by a few slides on different incidents involving pipe bombs and black powder.

INCIDENT STATISTICS FOR THE PAST FIVE YEARS

(The figures in italics indicate incidents involving black powder, fireworks or pyrotechnics)

	1991	1990		1989		1988		1987	
BOMBING ATTENTAT A LA BOMBE	114	103	*36*	69	*17*	83	*27*	88	*48*
ATTEMPTED BOMBING ATTENTAT MANQUÉ	44	31	*11*	22	*8*	24	*6*	15	*0*
RECOVERY OF IED DECOUVERTE D'ENGIN NON POSÉ	33	30	*15*	30	*16*	29	*17*	32	*18*
HOAX DEVICE ENGIN FACTICE	42	41	*7*	24	*5*	15	*4*	13	*1*
SAFE ATTACK PERCAGE DE COFFRE-FORT	12	3		1		4		7	
ACCIDENTAL EXPLOSION EXPLOSION ACCIDENTELLE	8	10	*7*	5	*1*	19	*9*	5	*4*
SUBTOTAL	253	218	*76*	151	*47*	174	*67*	160	*71*
ANNUAL % INCREASE	16%	34%		31%		27%		35%	
THEFT OF EXPLOSIVES VOL D'EXPLOSIFS	16	19		15		10		14	
RECOVERY OF EXPLOSIVES RÉCUPÉRATION D'EXPLOSIFS VOLÉS	46	29		38		36		29	
TOTAL NO. OF INCIDENTS INCIDENTS TOTAL	315	266	*76*	204	*47*	174	*63*	160	*71*
TOTAL NO. OF DEVICES ENGINS TOTAL	400*	350		198		220		203	

* This is an estimate because all our 1991 files have not yet been completed.

A breakdown of high and low explosives is not available, but it is expected that we will have passed the 400 mark in 1991 devices.

1987 STATISTICS

Category	Numbers	Filler
Bombings	Total 48	
	30	black powder/smokeless powder (pipe bombs)
	10	firecrackers, railway torpedoes fishing salutes, screechers, matches, military pyrotechnics
	8	homemade black powder
Attempted Bombings	Total 0	
Recovered IEDs	Total 18	
	13	black powder (pipe bombs)
	5	firecracker, match heads, railway torpedoes
Hoaxes	Total 1	
	1	railway fusee
Accidental Explosions	Total 4	
	3	match heads
	1	fireworks

1988 STATISTICS

Category	**Numbers**	**Filler**
Bombings	Total 27	
	10	black powder (pipe bombs)
	5	match heads
	12	Polar Bear. Screamer M-80. fireworks
Attempted Bombings	Total 6	
	4	black powder (pipe bombs)
	2	match heads
Recovered IEDs	Total 17	
	8	black powder (pipe bombs)
	7	match heads
	2	rocket motor/firework
Hoaxes	Total 4	
	4	railwav fusee
Accidental Explosions	Total 9	
	6	match heads
	1	railway torpedoes
	1	rocket motor
	1	black powder

1989 STATISTICS

Category	Numbers	Filler
Bombings	Total 17	
	15	black powder (pipe bombs)
	1	firecrackers
	1	match heads
Attempted Bombings	Total 8	
	7	black powder (pipe bombs)
	1	match heads
Recovered IEds	Total 16	
	8	black powder (pipe bombs)
	8	artillery simulator fireworks, whistler firecrackers, match heads, Roman candles.
Hoaxes	Total 5	
	4	railway fusee
	1	firecrackers
Accidental Explosions	Total 1	
	1	Roman candle

1990 STATISTICS

Category	**Numbers**	**Filler**
Bombings	Total 36	
	26	black powder (pipe bombs)
	3	match heads
	7	SC-82 fishing salute, M-80, firecrackers
Attempted Bombings	Total 11	
	7	black powder (pipe bombs)
	1	match heads
	3	railway fuse, moontraveller firecrackers
Recovered IEDs	Total 15	
	12	black powder (pipe bombs)
	1	M-80/firecrackers
	2	match heads
Hoaxes	Total 7	
	7	railway fusee
Accidental Explosions	Total 7	
	4	black powder
	1	trip flare (military)
	1	match heads
	1	home-made black powder

"ASPECTS OF DISPLAY DESIGN"

WILF SCOTT - MANAGING DIRECTOR

LE MAITRE FIREWORKS LIMITED,

FOURTH DROVE,

PETERBOROUGH,

ENGLAND,

PE1 5UR.

If you're not born into the firework business, the beginnings of peoples' involvement can be very diverse. Mine was via sculpture, film props and an art exhibition. I was not interested as a child in fireworks. I distinctly remember the cliche of the exploding box of November 5th fireworks when I was seven or eight. The grand spectacular had somewhat disappeared after the war and the coronation, the great tradition of the Brock family had almost vanished by the mid 50's in the U.K.

My first involvement was with what can only be described as fire sculptures, where the emphasis was on the pyrotechnic effects rather than coordinated displays. We had only tiny budgets and lots of time, so the construction side was cheap in those days. Now, alas, the opposite is true. Invariably our dragons or giants told a story always with the evil one getting his or its comeuppance in balls of fire produced by gas and pyro, with the use of more conventional material, i.e. shells and roman candles, as a finale over the burning pyre. The firework element was primitive and fast-against the convention of "time is value for money" which then prevailed, (as it still does!).

The Catholic baroque tradition of Southern Europe had not penetrated the somewhat calvinistic U.K. - fireworks were not a religious tradition in Great Britain. The approach was slow and often boring, turning an explosive medium into an uncoordinated series of effects without any of the flair of France, Italy or Spain, with the exception of the Lewis bonfire societies.

From our own small beginning we were invited by Chris Philip to perform cameo parts within what was the largest show in London at the time, at a Leisure Centre at Pickets Lock. Although we were a separate entity with our special effects, I couldn't help noticing the different approach of Chris and his team. Electric firing system, multicore cables, large frontages with volleys of shells from two or three positions, and, of course, the material. Chris had begun importing Maltese material from Charlie Briffa and there were roman candles from Hendrix in Belgium. The quality of the material was so much better than that which we had been using. Naturally, we started to buy material from Chris, and he began to use us as crew. The turning point was at Wembley Stadium, where the requirement was to fire small set pieces and wheels, etc, at either end of the stadium electrically in time with the music of massed military bands.

The organiser was so pleased we were invited to Oman in the Gulf to do a repeat performance at the tattoo. These shows were quite French in their arrangement and were to music - few people in the U.K. were doing this kind of work at the time. The result of this visit got us involved in the Oman national day celebrations, which involved many shows up and down the Country, with no roads and often little understanding. A lot of the best schemes were shelved as the pressure to get a show off in what were often wild conditions. Portfires were produced to overcome the lack of set up time.

The shows that were electric were on the forts of Mharani and Mutrah. The first being Muscat, the second in the neighbouring port of Mutrah - both on the same night. As the last volley of shells hit the sky in Muscat we were bundled into police cars, lights flashing and sirens wailing, and hurtled along less than adequate cliff roads to the next castle, up the 102 steps and, wallop, start all over again. The content of these shows consisted of mainly Maltese cylinder shells with Ruggieri and Parenti candles, Brunchu rockets and Japanese type shells. Budgets for those days were big and the amount of material enormous in comparison with the U.K. market. Firing was often done with a nail board and batteries, which limited the ignitions on a frontage, but allowed for rapid assembly with copious bundles of quick match. From Oman we picked up work in Bahrain, Qatar, Abu Dhabi and Sharjah. Out of all of these venues Oman remained the favourite, finally offering the chance to fulfil an ambition of shooting from three points in Muscat Harbour for the Queens visit to the Middle East. Our position was an Island at the tip of the bay. All went well with the show, but security was so tight that the police arrested our rescue boat and we ended up stuck there. Other places out there lacked the beauty of Oman, although Bahrain had charm and access to Double Diamond - we regarded Bahrain as a second home.

Other places had problems like 140°F, and situations where the show is all set to go and we are ordered to move it 50 metres sideways, the reason being that the gentleman asking was the police chief, and nobody told him about fireworks, and one thing you learn very quickly is "Don't argue with Middle East police chiefs!"

Most of these shows were fired on the old nail board and battery principle - crude but effective. In retrospect a lot of these shows relied on power and volume, and were very Valencian in shape, (circa 1970-75). The design element had the luxury of big budgets and lots of material. It was before the availability of Chinese material in the U.K., which resulted in the smallest candle being 30mm with frequent use of Panzera 60mm. Rockets were shot Valencian style out of steel cones, dozens at a time, the largest volley being 470 dozen simultaneously in Abu Dhabi, a truly awesome sight.

It is possible to have learned something in this business by the time you're eighty, but there would, I feel, be a lot left unseen and surprising. The more we visited Europe and saw the way different Companies solved the same problems, the more I realised that we were only at the beginning. Although I had good grounding in handling large volumes of material in often near impossible circumstances, it became more and more important to develop the design and the flow of shows rather than to rely solely on power. Nevertheless, probably every show designer has to go through the power phase as bigger, more sophisticated shells are discovered. Indeed I still get a buzz with 10 x 10 inch shells in the sky at the same time with rockets underneath.

The Rolling Stones 1982 European Tour taught me a lot about European fireworks, not so much the show itself, which was purely artillery, but for the introduction to other companies with different styles. During this period we competed in the October pyrotechnic festival in Valencia, where I saw a finale sequence designed by Louis Brunchu which, to my mind, was one of the most poignant sequences I have ever seen. I would think the duration was approximately 1 minute. The equipment was laid across the boulevard, possibly ten lines starting with 80mm green and silver shells. This was a rapid fire sequence with hundreds of bombs until you felt that it was out of control, just green and silver with 100mm shells to lift the height a solid 45 seconds until your eyes popped and I found myself backing away. Then 500 x 75mm maroons on match and, as they began, 200 to 300 16mm Perlas Blancas rockets cascading over the top of the green and silver. The idea was as simple as it was beautiful. The green and silver represented the sea growing into a wave, the maroons, the wave crashing onto the beach, and the Perlas Blancas rockets, the white foam as the wave crashed.

That was the first I had seen of this new, literal, sequence. Since then, the river bed shows at the Fallas have incorporated some extraordinary sequences of equal frontage and strength, but the first one will always be the best.

As a freelance designer I sold the idea of a big show in Hyde Park and I needed a contractor. Le Maitre offered to help. Firing systems were the key to the concept as there had been a lot of grumbles about the Royal Wedding fireworks, (nothing to do with me), because people complained they couldn't see. I decided to go for a pontoon lay out with a bigger calibre show from behind the stage. There were two pieces of music, Handels water music and Handels firework music. The water music was situated on the serpentine on five metre pontoons, such that when the material fired it would occasionally take on the shape of a pyramid but, whatever sequence fired, it would look the same from all four sides - from the bridge on the lake, the river banks, and the cameras on stage. The firework music display was to come from behind the stage and, as a finale, both sides would fire together. The finale of the first section was a 250 metre waterfall requiring two 100 ton cranes to hold it up.

We used 1000 metres of multicore cable from a central firing position with a slave unit on each barge, and one out in the back stage area. The waterfall was fired by an industrial quarry blaster. It worked, and all would have been perfect if the central pontoon hadn't caught on fire and almost sunk, with 8", 10" and 12" shells on board. A rapid row and the pontoon was boarded, unfortunately the boatman panicked and threw the 10" overboard. Although it was a lake, there was a slow current flowing under the barge, which meant that the shell could float under the fire. Fortunately the fire brigade arrived on a small boat with an outboard motor which cut through the multicore, isolating the burning pontoon from the switchboard. So off we went to check a few burning candle cases. Meanwhile I am peering into the blackness to try and locate the ten inch.

The show continued to roll all around us, lighting up the second world war mine shape of the ten inch bobbing about. I discretely suggested we check it and retrieve it, much to the reluctance of the firemen. We did so, but it proved too much for the little boat and a fountain of water shot up through what had been a mast hole. With one hand over the hole and the ten inch shell clasped firmly between my knees, we reached the shore just as the waterfall exploded into life. Phew!

The music business has provided a lot of work over the years, Rock and Roll in particular. The first tour I ever did, (nothing like being dropped in at the deep end!), was with the Pink Floyd 'Animals' tour in the U.S.A. and Canada. We had originally been asked just to build sheep and pig shells. Tim Hunkin, (the man I worked with in the beginning with fire sculptures), and myself had been asked to build flag shells of sheep and pigs. Finally, after realising there wasn't enough Japanese tissue paper in the Country to complete the task, Chris Philip came up with good old British tea bag paper which we could heat seal. The sheep were to be ten feet long and three dimensional. We loaded them into cylinder shells and we thought that was that, but then the band decided they required an operator so off I went.

I had never been to America before and I found myself totally disorientated, like being in a T.V. serial without being able to switch it off! I suppose a 20 truck rock tour is not the best way of seeing a country. Needless to say, all my material was held up in customs, so there I was in Miami, a long way from home, without any sheep, let alone pigs. Fortunately somebody found a flight case sent from England by mistake, which was full of pyro from an earlier Roxy Music tour. I had no idea what it was so off I went down the car park to do some tests.

I found gerbs and waterfall cases, some festering flash powder and "stuff". I had to start inventing a stage show, as people were asking questions about what I was doing there as the material was impounded. I stuck gerbs upside down on the cherry pickers, bought more waterfall cases from Zambelli, and rigged a 300 foot waterfall behind stage. With odd bits of flash for other songs, this was the baptism of fire in stage work. By the time my sheep caught up with me I had bought, borrowed and glued together all manner of things, and the waterfall had become a regular feature. With 500 sheep to deal with as well, I was pushed to get everything done by show time. So, in Cleveland, I decided to shoot 150 sheep to lighten my load, as my one flight case had grown to six with 8" Maltese cylinders and all sorts. I was supposed to shoot only 5 sheep from the bleachers, but I borrowed hundreds of tubes from Jim Sorgay of American Fireworks. I let them go in 5's with a pyro delay - on and on the sheep went through most of the first half of the show. People were sent to shoot me but I told them "you can't stop it once its started!" (I needed the space and they had taken hours of work). The management also asked me to shoot down a helicopter, which I missed. I was still wandering around with my tea caddy full of batteries and nails, much to the disgust of the high tech lighting crew.

Upwards and onwards. I had to return to England to rig shows for the Queen's Jubilee, sadly not the magical show for Peter Budric on the Thames. I was very impressed by his equipment design - it proved to be a great influence, as were his concepts of firework displays. I felt there was an ally out there.

The Rock and Roll years have virtually developed into Rock Minutes, as Le Maitre is deeply involved in the supply and use of material for Rock Tours. European work has included the last Stones tour, with a design concept originated in the U.K. so that the effects would be compatible worldwide, the Tina Turner European tour, and currently, supply only to Simply Red. I feel the Rock world requires a special kind of chap - at 46 I feel I am almost over the hill for shinning up 70ft towers, doing the upside down routine on trusses, staying awake for 23 hours doing a show and then packing it all up again with the promise of instant death if you miss a cue or singe a star. However, I still enjoy the big Rock stage. The element of design, and systems to fire the concept, are in an embryonic stage and will develop considerably in the next few years. One of the most satisfying hits in Rock and Roll was the firing of 500 Blinker bombs in 20 seconds on "The Wall" concert in 1990 in Berlin. Zinc blinkers are the best!

The year 1990 had some very special shows. We won the contract for the Forth Bridge Centenary, which had it all for me - steam trains as part of the show and a bridge which is one of the engineering wonders of the world. Knees trembled as we did the site visit and the railway company explained how we would have to work - no, we can't close the bridge where there are 200 trains a day, yes, you will have to go on a railway safety course, and no working after dark or in high winds.

We appreciated the latter as a 200mph wind with ice and razor blades knocked the stuffing out of us in October, as the jetty collapsed on Inchgarvie, the Island in the middle of this one and a half mile structure.

"Fight on!" was the cry in Swedish, French and English, (the crew was 16 men from four countries and trained in survival and train dodging). we had to fire the full length of the bridge at least twice. We managed it three times, and laid 16 miles of cable to achieve it. A once in a lifetime experience.

Whilst in Scotland, a mention of 'Glenlivet' show in Edinburgh cannot be avoided. The show has been a milestone in my life with an audience of at least 200,000, and at best, 300,000. It's the largest classical music and fireworks concert in Europe and its live. They change the conductor every year and sometimes he speeds up and sometimes he slows down, and we all panic. With one and a half tons of NEC material, 12 miles of cable, and two firing positions it can all be a bit overwhelming. However, no other central town site has what Edinburgh has, the Castle and one side of the street missing, so the natural auditorium of Princess Street and Gardens provide a massive viewing platform. Also, with a sponsor like Seagrams, who have continually invested in this event, and an unpretentious and cooperative orchestra like the S.C.O to work with, its a great deal of responsibility to live up to. We try, we do try.

River work in London, atmospherically, is always a joy on a summer evening. To be floating down the Thames with a couple of barges and the great tug-men after a successful show is magic. Thanks to Linda Macfadyen at the Festival Hall we got a chance to do Thames Day and Winters End. Rarely do you work for people who not only love the result of what you do, but also listen to how you think it should be done. With Linda's Winters End show (idea to celebrate Valencia in Fallas), with budgets of £30,000 and an order not to last more than 10 minutes, we had fun. It was a happy and entertaining relationship.

P & O. 150 Years was done under different management, and in the presence of H.M. The Queen. It was one of the first coordinated, multi media shows on the river with lasers, lighting, model ships, fireworks, music and dialogue. Powerful stuff, pageantry, history, etc, but not totally satisfactory from our point of view, as the big shell barge was off down the river from the candle and small calibre barges. The reason for this was that the Queen would not go into a covered part of the ocean liner parked opposite the firework barges - the height of the top deck would have put H.M. in line with 6", 10" and 12" shell casings. I had to hire a crane with a basket so that we could video what happens when you are at the bursting height of big shells in adverse weather conditions. After forty seconds the video produced great pictures of the ground, as the camera man dropped it and hung on for dear life with the crane cage rattled by shell casings and stray stars.

From that gesture of consideration, I have since done the Queens Private Ruby Wedding party with only eight guests. The show was all red and pink laid out like a garden in spring. Why is it that policemen like to tell you the make of their machine guns? Security was tight!

In 1991 we finally got our hands on Buckingham Palace to shoot with music for the G7 Conference in London. I have shot round it, near it, but never on it. The officials were less than pleased with the concept - it seems that the people who live there like the place, and had no wish to burn it down. Many, many meetings later, and even a call from the C.I.A., permission was granted.

We were asked to use the roofs and the internal courtyard. The roof material was only icing on the cake. It was all the internal balconies that carried the bulk of the show. Every balcony, balustrade and gutter was wired up with something, the cable looms were a nightmare, as was the presence of 300 musicians below them, 2000 press men, and the World leaders on another balcony at the other end of the courtyard. The biggest problem we had was the insistence that they use the biggest Royal Standard available, which extended 20ft and over some of the material. I don't know what the punishment is for burning it. This question was posed by the Queen. I am glad neither of us had to find out.

Displays will continue to develop, with digital timing, midi computer systems, new material and new people with new ideas. That's what makes the industry so fascinating. It's a never ending quest in the hope that one day you may produce the perfect show. I haven't yet, but I live in hope.

IGNITION SENSITIVITY OF FIREWORKS COMPOSITIONS

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ABSTRACT

Fireworks compositions may encounter a variety of ignition stimuli during the manufacturing process, including friction, impact, heat, and static electrical spark. Compositions vary in their ignition sensitivity for a number of reasons, including the selection of oxidizer and fuel, purity of the chemicals, weight ratio of chemicals, extent of mixing, and the particle size of both the starting chemicals and the granulated mixture. Variation in any of these factors from batch to batch can result in a change in the sensitivity of the mixture, thereby creating the possibility of an incident. Compositions will also vary in their sensitivity to the specific type of energy that encounters the mixture. A particular mixture may be quite sensitive to one type of energy input, such as spark, while displaying excellent thermal stability. Sensitivity data for various compositions will be examined, and general sensitivity theory will be discussed. Modern methods of thermal analysis have been of particular value in assessing the thermal sensitivity of fireworks mixtures. Methods of altering the sensitivity of fireworks compositions will also be examined.

INTRODUCTION

The "sensitivity" of a chemical mixture used to achieve a specific visual, audible, or propelling effect in a fireworks device is a matter of great interest to the manufacturer, who has a significant investment in plant facilities and, of course, a genuine interest in the safety and health of plant employees. Many of the formulas used by fireworks manufacturers have evolved over years of production and have been adjusted from time to time as changes have occurred in the fundamental nature of the raw materials used to produce the mixtures. The fireworks industry uses few, if any, chemicals that are specifically manufactured or processed for fireworks manufacturing. The industry uses materials that have been manufactured to meet a specific military pyrotechnic specification or it uses materials that have been produced for totally different, nonpyrotechnic purposes. It is also sometimes the case that fireworks manufacturers are offered a special "deal" on chemicals that fail to meet a rigid military specification, but are otherwise suitable for use in fireworks mixtures.

During the fireworks manufacturing process, chemicals are initially mixed to produce a reasonably homogeneous blend of oxidizer, fuel, color-enhancing chemicals, and binder. These mixtures are then pressed into tubes, processed into cubes or cylindrical "stars" for aerial color effects, or otherwise used in the manufacturing process. During these operations, it is possible that the chemical mixtures will experience impact, friction, spark, and heat. It is therefore extremely important that the manufacturer have knowledge of the sensitivity of each chemical mixture to these various types of energy input.

The fireworks industry has gradually eliminated chemicals that have acquired a reputation for repeated involvement in hazardous incidents during manufacturing. The virtual elimination of "Paris Green" - a copper/arsenic compound - for employee exposure reasons is one example of this trend. Many manufacturers have also eliminated or minimized the use of potassium chlorate or barium chlorate as oxidizers in fireworks mixtures. Chlorate mixtures, particularly with sulfur, have acquired a well-deserved reputation as unstable mixtures, and fires and explosions can be anticipated if these materials are included in manufacturing operations.

No fireworks composition should be deemed truly "safe", however. All fireworks compositions are designed to function by burning or deflagration (very rapid burning), and a mixture that does not release its energy rapidly when exposed to a piece of lit fuse or other ignition source will be of extremely limited value. Fireworks manufacturers must have technical data on the sensitivity of their mixtures to ignition from various stimuli, and they must then analyze their manufacturing process to determine all of the possible sources of energy that compositions might experience during mixing, loading, and assembly into finished fireworks.

The ignition sensitivity of fireworks compositions can vary considerably, depending on the type of energy interacting with the chemical mixture. It is necessary for a given energy input to be efficiently transferred to the composition for ignition to be achieved Energy input may occur via impact or friction, and thereby be mainly kinetic energy in nature. A spark is a combination of thermal, electrical, and shock input, while flame or heat involves the application of thermal energy. To achieve ignition, it is necessary for chemical bonds in the mixture to absorb a sufficient quantity of the incident energy for bond breaking to occur. This energy transfer frequently involves raising the vibrational energy of various chemical bonds in the starting materials to the point where the restoring force is overcome, and the bond breaks. More stable chemical bonds then form and a net release of energy occurs. If this released energy is sufficient in quantity and is efficiently captured by adjacent layers or grains of blended chemical composition, the ignition process is repeated through the mixture, and propagation of the burning reaction is achieved with no additional input of external energy required.

Two key components to the "sensitivity" of a given mixture are the ignition temperature and the heat of reaction of the composition. Ignition temperature is defined as the minimum temperature necessary to achieve a rapid, self-propagating pyrotechnic reaction that proceeds on its own with no additional external energy input required. Ignition temperature measurements can be determined by several methods, including thermal analysis. Heat of reaction reflects the amount of heat, in units of kilocalories or kilojoules per gram, that is produced when a given mixture ignites and burns. Heats of reaction are conveniently measured in an apparatus called a "calorimeter"; the atmosphere selected for the experiment is important, to the extent that atmospheric oxygen plays a role in the overall combustion process for a mixture.

Sensitivity testing of pyrotechnic compositions generally involves the determination of the sensitivity of a given mixture to four types of stimuli: elevated temperature, impact, friction, and electrical spark. A variety of specific types of test equipment have been developed over the past fifty years for measuring sensitivity, and it is unfortunate that a universal test fixture for measuring each type of sensitivity has yet to be agreed upon by the international explosive and pyrotechnic community. It can therefore be difficult, if not impossible, to directly compare impact or friction sensitivity results obtained on different types of test equipment. Relative rankings of sensitivities generally bear some semblance of order, but any quantitative comparisons are impossible. Spark sensitivity values correlate a bit better when a minimum ignition energy, in joules, is determined. Test conditions still play a significant role in the absolute value of spark sensitivity measurements, however, and standardization is needed in this area.

Experience has shown that the presence of certain fuels in pyrotechnic mixtures tends to cause the resulting mixtures to have significant sensitivity to spark. Zirconium, boron, and phosphorus are particularly noted for their spark sensitivity. Fine magnesium or aluminum powder can enhance spark sensitivity, and fine grains of blended oxidizer/fuel mixture will have a significantly greater sensitivity to spark than coarser grains. This is of importance to manufacturers, because there is always the possibility of generating fine pyrotechnic dust during processing. In general, the mixtures used in fireworks compositions tend to display spark sensitivity values that are in the "moderate" range. In assessing spark sensitivity hazard, a value of 0.10 joule or less for spark ignition energy is often regarded as indicating a spark sensitivity concern requiring a full static protection program. Values for a series of fireworks compositions are given in Table 1. It can be seen that these values tend to be considerably greater than 0.10 J.

Friction sensitivity studies have shown a relationship to ignition temperatrure and heat of reaction, but the critical factor in friction sensitivity appears to be the presence in a composition of a significant amount of a "gritty" or hard, granular component. This material, when rubbed, will generate "hot spots" that can led to ignition. Conversely, the presence of a soft, lubricating chemical such as a wax can significantly reduce friction sensitivity. The lack of a standard, quantitative method of evaluating friction sensitivity has limited detailed evaluation of this type of energy input, but friction is always a concern when fireworks compositions are pressed into tubes. The proper alignment of tools and equipment used in pressing operations is very important in minimizing the possibility of a friction-related incident.

Thermal sensitivity is the most reproducible of the various types of sensitivity tests, owing to the relatively minor effect of the specific test conditions on the value that is obtained. Ignition temperature measurements determine the minimum temperature at which a composition begins to react in a rapid, exothermic, self-propagating manner. Such measurements are based on the exposure of the sample material to a continually-increased temperature, and the experimental method is affected to only a minor degree by the particle size, blended grain size, degree of confinement, extent of mixing, and even the testing method and heating rate that is employed. Ignition temperature is therefore a fairly reproducible number from laboratory to laboratory as well as from country to country. The reproducibility of ignition temperatures is usually within 50°C from one study to another.

Thermal sensitivity is a useful value for a fireworks manufacturer to know for several reasons. First, it gives an indication of the potential hazard represented by exposure of a given composition to elevated temperature during mixing, drying, and storage. Secondly, it gives the manufacturer an idea of the ignition transfer problems that a given formulation is likely to present. Stars that are difficult to ignite typically have high ignition temperatures of 500°C or more, while easy-to-light stars usually have ignition temperatures substantially lower in value. Many chlorate-based stars, long valued by the fireworks industry for their ease of ignition and reliable propagation of burning, may have ignition temperatures below 200°C. Their ease-of-ignition benefit during firing is offset by their sensitivity to ignition during manufacturing, however.

The availability of moderate-cost thermal analysis equipment has proven to be a great aid to researchers investigating fireworks chemistry over the past several decades. Ignition temperatures can be readily obtained and the underlying chemical phenomena that lead to the initiation of the ignition process can be analyzed. These studies may permit the subsequent enhancement of thermal sensitivity for hard-to-light mixtures or enable the manufacturer to elevate the ignition temperature and thereby desensitize a mixture by appropriate modification of the chemicals used.

Thermal analysis provides a thermal profile as well as a thermal fingerprint for any type of solid material, including fireworks compositions. A sample is heated at a constant, programmed rate (typically 20-50°C per minute) while either the sample temperature or heat flow is monitored versus a thermally-inert reference material. In differential thermal analysis (DTA), the sample temperature is compared to that of the reference, while differential scanning calorimetry (DSC) measures relative heat flow. The resulting plot of temperature difference or heat flow versus temperature can then be examined to determine the thermal events that occur in the sample during heating. The typical temperature range examined in such studies is ambient to 500°C, although higher temperatures can be studied with heat-resistant sample holders and related equipment. Physical transitions such as melting points, solid-solid crystalline phase transitions, and boiling points are observed as peaks in the thermal profile (termed a "thermogram"). A reaction between components that liberates heat - such as the ignition of a fireworks composition - is also readily detected by thermal analysis methods. This ability to detect both endothermic (heat-absorbing) and exothermic (heat-releasing) events enables the thermal profile of a mixture to be obtained. The individual components that make up a mixture can often be recognized by their specific melting points or crystalline transition temperatures, while ignition temperature is recognizable by the onset of a rapid, heat-releasing process.

Analysis of the thermograms of numerous pyrotechnic mixtures has indicated that the thermal activation of one or more of the components of the mixture is required for ignition to occur. Mobility - the ability for one component to intimately mix with another - is important; oxidizer and fuel must be in intimate contact for a rapid reaction to ensue. Melting, boiling, and decomposition temperatures are therefore quite important to the ignition process. Melting exposes fresh, reactive surfaces and creates the fluid, liquid state. Intimate mixing is facilitated by melting, while vaporization allows mixing to occur at an even faster rate.

Many of the oxidizers used in fireworks compositions melt at relatively low temperatures (Table 2), and melting of the oxidizer often precedes ignition. The melting process of a pure material can be detected by thermal analysis as a sharp endotherm. Significant release of oxygen by the oxidizer is frequently associated with the onset of melting by the solid material. A thermal analysis technique known as thermal gravimetry, which monitors any change in sample weight as a function of increasing temperature, can be used to study the release of oxygen by a sample of pure oxidizer.

Metal fuels, in general, have higher melting points than fireworks oxidizers, and the metal is often protected by a surface oxide coating that retards further oxidation of the metal by the oxygen released by the oxidizer upon heating. The oxide coating is lost as the metal fuel approaches its melting point, and fresh, active metal surface is exposed. Rapid oxidation follows. Hence, oxidizer/metal compositions frequently display ignition temperatures quite near the melting point of the metal.

Organic compounds consisting of carbon, hydrogen, oxygen, and nitrogen - often used as fuels and binders in fireworks mixtures - are typically characterized by decomposition temperatures in the 250-350°C range. At these temperatures, the weakest chemical bonds in the organic molecules break, forming very reactive fragments known as "free radicals". These fragments tend to be quite susceptible to oxidation, and are converted to carbon dioxide and water by reaction with atmospheric oxygen or with oxygen released by the thermal decomposition of a solid oxidizer. This oxidation of the organic fragments releases heat, raising the overall temperature of the system. This temperature elevation then accelerates all of the decomposition reactions. More heat is liberated and the overall process is sent into an upward spiral, leading to ignition and propagation of burning.

A mixture consisting of an oxidizer, metal fuel, and organic binder can therefore display interesting ignition temperature behavior. At low percentages of binder, the heat released by the decomposition and oxidation of the binder is not sufficient to activate the metal fuel by raising the sample temperature to the metal's melting point. With higher binder percentages, the low temperature reaction between oxidizer and binder may be sufficient to activate the metal, leading to an ignition temperature several hundred degrees below the ignition temperature of a binary mixture of metal and oxidizer. The binder is not only providing mechanical strength and cohesion to the mixture, but it may also thermally sensitize the mixture by providing a low-temperature fuel. It is for this reason that changes in the formula for a given fireworks effect must be watched carefully. A mixture with 2% dextrine may have an ignition temperature considerably higher than the same mixture with 6% binder. Minor changes in the percentage of oxidizer or metal fuel will have no such effect on the ignition temperature; the melting points and decomposition temperatures of the two materials control the ignition process. Ignition temperatures for various fireworks mixtures are given in Table 3.

Similar "minor" changes may also affect the spark and friction sensitivity of fireworks mixtures. It is therefore important to reassess the sensitivity of a composition anytime that a change in formulation is made. It is especially important to reevaluate sensitivity if a chemical substitution or replacement is made, such as the replacement of aluminum by magnesium/aluminum alloy. Sensitivity values should be determined, and a new or revised mixture determined to be acceptable, before any new mixture is prepared and processed in large quantity. The evaluation of sensitivity and an understanding of the need to reevaluate sensitivity anytime that a change is made in a fireworks mixture is another important step in advancing the art, science, and safety of fireworks into the twenty-first century.

TABLE 1. Electrical Spark Sensitivities of Typical Fireworks Compositions

The minimum ignition energies, in joules, for a series of fireworks compositions are presented in Table 1. These values were obtained on 20 milligram samples using a device patterned after the U.S. Bureau of Mines electrical spark apparatus. The value reported is the minimum energy at which at least one sample in ten ignites. These values were determined by Mr. Fred McIntyre of Sverdrup Technology, Inc., Bay St. Louis, Mississippi.

Composition	Minimum Electrical Spark Ignition Energy, in joules
Black Powder	3.125
Gold Comet Powder Potassium nitrate, charcoal, sulfur	2.205
Silver Cone Fountain Composition Potassium nitrate, charcoal, sulfur, flitter aluminum	1.805
Red Stars Potassium perchlorate, strontium carbonate, red gum, charcoal	0.685
Green Stars Potassium perchlorate, barium nitrate, red gum, charcoal	1.620

TABLE 2. Melting Points of Common Fireworks Oxidizers

Most of the oxidizers used in fireworks compositions have melting points below the melting point of aluminum, the most commonly-used metallic fuel found in fireworks compositions.

Oxidizer	Melting Point, ^{o}C
Potassium Nitrate, KNO_3	334
Potassium Chlorate, $KClO_3$	356
Strontium Nitrate, $Sr(NO_3)_2$	570
Barium Nitrate, $Ba(NO_3)_2$	592
Potassium Perchlorate, $KClO_4$	610
Aluminum metal (for comparison)	660

Source: Handbook of Chemistry and Physics, 63rd Edition.

TABLE 3. Ignition Temperatures of Typical Fireworks Compositions

Ignition temperatures determined by differential thermal analysis are presented below. These values represent the temperature at which a strong exothermic reaction appears in the thermogram of the mixture. An audible effect can be heard during many of these trials, indicating a violent reaction.

Composition	Ignition Temperature, °C
1. Chinese firecracker composition Potassium chlorate, sulfur, aluminum	150
2. Potassium chlorate, sugar	200
3. Black powder Potassium nitrate, charcoal, sulfur	340
4. Flash powder Potassium perchlorate, sulfur, aluminum	450
5. Gold sparkler composition Barium nitrate, aluminum, dextrine, iron filings	>500

EVALUATION OF FIREWORK MORTARS

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ABSTRACT

The objective of this study was to evaluate the performance of firework mortars by causing shells to explode in them. Tests were performed at nominal temperatures of 20°C and -20°C for both star and report shells. Events were recorded via video, still and high speed photography. The results do not indicate serious faults with any particular mortar material.

The study reports the results of approximately 280 mortar bursts and attempts to relate the data to several concerns. The requirement for a maintenance-free mortar, one that can withstand repeated use and, in case of a failure, a "fail-safe" mortar. Thus, when it comes to use, an operator must always make a judgement as to whether a paper mortar can take another firing. Steel mortars have always been relied upon to take many firings yet everyone realizes the degree of danger if one was to burst.

The results indicate that all mortars, except the Schedule-40 steel which burst only at very low temperatures, ruptured and produced fragments under most conditions. However, when one considers the consequences of an accidental burst, the mass and distance to which fragments were thrown can be used as safety criteria. The fragments from the fibre reinforced epoxy mortars had a range of approximately 30 m, the paper 70 m, the plastics 70 m and the metal mortars 120 m.

ÉVALUATION DE MORTIERS POUR PIÈCES PYROTECHNIQUES

RÉSUMÉ

Cette étude avait pour but d'évaluer la résistance de mortiers à l'intérieur desquels on a fait exploser des bombes. Ces essais ont eu lieu à des températures variant de 20°C à -20°C, tant pour les obus à étoile que pour ceux à fort détonation. L'éclatement des mortiers a été enregistré sur band vidéo, sur photographies prises à grande vitesse et sur photos empruntées à un film. Selon les résultats, aucun mortier ne semble présenter de défectuosité grave.

L'étude rapporte les résultats d'environ 280 tirs de mortiers, résultats qu'elle tente d'évaluer selon divers critères. Le mortier idéal, par exemple, ne nécessite pas d'entretien, peut être utilisé trés souvent et offre une "sûreté intégrée" en cas de défaillance. Ainsi, chaque fois qu'il utilise un mortier en papier, l'artificier doit juger si ce mortier d'acier pour affectuer le plus grand nombre de tirs, on sait bien quel danger celui-ci représente s'il vient à éclater.

Au cours de ces essais, les mortiers ont tous éclaté en fragments sous le choc des explosions auxquelles on les a soumis. La seule exception est le mortier d'acier, de type Schedule-40, qui n'éclate qu'à de trés basses températures. Cependant, si l'on tient compte des conséquences d'un éclatement accidentel, on peut retenir, comme critère de sécurité,la masse des fragments et la distance à laquelle ils sont projetés. La portée des fragments variait selon la composition du mortier: époxy renforcé de fibres: 30 m; papier: 70 m; plastique: 70 m; métal: 120 m.

INTRODUCTION

The aim of this study was to evaluate the performance of the mortars that are currently on the market and make recommendations as to the best performers and modifications that may best improve their safety in use. This was accomplished by causing various sizes of shells to explode in mortars of corresponding sizes and made of the different materials normally in use. Tests were performed at nominal temperatures of -20°C and 20°C. This work (1) is comprised of a rather lengthy report, two albums containing in excess of 500 photographs and a three hour video which includes high speed photography.

During the past few years, the fireworks industry has become particularly sensitive to the safety of their operations. The reasons for this may be;

1. society's increasing awareness of safety and, in its drive to reduce injuries has led to more stringent labour codes,
2. skyrocketing insurance rates, and
3. fundamental economics.

In the past, operators manufactured mortars from whatever materials were available in the marketplace. At present, the authors are aware of only two mortar types that are manufactured from basic materials for this very specific function in North America. They are, the sheet steel with integral bottom and the moulded HDPE. Another mortar is being manufactured from specially made HDPE pipe and a hardwood plug that are rigidly fastened together with through-bolts. Two other types that could also be considered in this category are steel pipe with welded bottom and High Density Polyethylene (HDPE) pipe with welded HDPE caps.

As part of a major thrust by the Canadian Explosives Research Laboratory (CERL) to investigate concerns in this field, (1-7) support was obtained from various firms including the American Pyrotechnics Association (APA). The APA began testing mortars in racks in 1989 and have produced a valuable video on this topic. CERL decided to take the more fundamental approach of evaluating individual mortars.

The program was defined to include approximately three tests on each of 76, 102, 127, and 155 mm mortars made from the most common materials, at two nominal temperatures, and tested with two types of shells. The two 'standard' shells included a star shell renowned for being quite energetic and available in 76, 102, 127, and 155 mm and a report shell available in 76 and 127 mm sizes. A parallel and related study, cited as reference (3), determined the TNT equivalent of the above report shells.

The question will undoubtedly arise as to the statistical meaning of the results given so few tests per specific set-up. A study with the outlined scope will have some shortcomings, however, attempts were made to temper this with careful data collection.

Although, most mortars perform well under normal circumstances, the results of this project indicate that some may be better than others in certain situations when one considers the lethality of the fragments from an accidental burst. Thus, the study can be used as a guide and as a starting point for the many questions that it has given rise to and that must be answered.

WHAT CONSTITUTES A GOOD MORTAR?

At the very conception of this program, the question arose as to what characteristics constitute a poor or alternately, an ideal mortar. What traits would disqualify a mortar from being considered as adequate?

An ideal mortar would be a tube (with bottom) capable of withstanding very high pressures but would have no mass (just in case it ever burst). One can only guess at the performance of such a mortar. For practical and safety reasons, a mortar should also be as maintenance-free as possible.

Since two phases must be considered when evaluating the effectiveness of mortars, first, the ability to withstand the high pressures and secondly, the lethality of the fragments if the mortar fails, then, the choice should be based on a balance between (1) materials of high strength and (2) "fail-safe" type materials (materials that would absorb sufficient blast energy to reduce the lethality of the fragments). Although, a relatively light mortar could be manufactured, the unrealistic opposite could also be considered. That is, a very massive mortar designed to withstand pressures higher than those developed by exploding fireworks shells. Since such a mortar is not practical, manufacturers initially attempted to achieve the high strength by turning to steel. Confidence, development of new materials and economics led to substitute materials. However, due to high development costs, research into a high strength, low mass mortar has not occurred.

And now, questions regarding the 'plug'. What is the role of this rather massive component? In this study, one plug was thrown 85 m! What kind of wood and grain orientation is best? Do mortars with integral plugs perform any better? Whenever such questions arise, the most common comment and reminder is that mortars are normally buried. This is true, but there are reports of plugs being thrown when mortars in racks or buried in snow or in sand boxes have accidentally burst.

The fastening system must also be considered when evaluating mortars with plugs. Arguments can be given for light or rigidly fastened plugs. The fasteners themselves can be questioned. Although screws and bolts make better fasteners, they are normally more massive than nails or staples. Again, the best plug/fastener system should minimize the number of lethal fragments in an accidental burst. And again, proper burial of mortars could render most mortar burst accidents safer.

Comments made throughout this report derive from the view that a rigidly fastened plug is the safest. Although this is not necessarily the case, this must be taken as a reference for two main reasons. First, manufacturers tend to strive for the best fastener system in the belief that it will increase the strength and the life expectancy of the mortar. Secondly, it is practically impossible to manufacture a mortar with a built-in weakness that would guarantee a "fail-safe" mode in the case of an accidental burst. The authors are not aware of anyone who is manufacturing a mortar with a built-in weakness as a safety design feature.

EXPERIMENTAL SET-UP

Two sets of preliminary tests were performed. The first was to establish how the mortar should be set-up to obtain reproducible data and to determine the effect of fragments on pressed paper board witness screens located 2 m from the mortar. Tests were performed with star and report shells at ambient temperatures with the mortar located upright on a concrete pad. The results reported in reference (1) indicated that this would not be a suitable set-up.

The second set of preliminary tests was performed with the mortars hanging within a frame. These tests were performed at ambient temperature to evaluate certain mortar materials. The results led to the test arrangement and procedure described below.

Basically, as indicated in Fig. 2, a mortar was hung in the centre of a series of 60 cm wide by 240 cm high frames, arranged to form a 3.5 m diameter circle. The frames, placed on a gravelled pad, held witness panels that would catch the fragments if the mortar burst. Seldom were all the frames fitted with witness panels since extensive damage was often caused by the blast pressures. As a result, a minimum of three panels were frequently used. Markers were placed on the ground at 5 m intervals from the mortar location to facilitate recording the fragment distance.

The mortars were hung so that the centre of the test shell in the mortar was 1 m above the ground. This height corresponded to the height of the blast pressure gauge which was located at a distance of 2 m. A steel wire was initially used to hang the mortar. In certain tests, the force from the lift charge caused the wire to break and the shell to burst in the mortar when on the ground. Sometimes, the explosion of a star shell would damage the suspension system and rocket the mortar toward the ground. A 155 mm steel mortar was driven (Fig. 2) approximately 30 cm into the ground. Consequently, progressively heavier wire was used, eventually switching to a chain bolted to the mortar.

All the data was recorded photographically and with video. A side-on pressure gauge was used to monitor the blast overpressures and some 30% of the tests were recorded with a high speed camera running at 500 frames per second.

When the mortars were first received, they were labelled and weighed. Two holes were then drilled close to the opening to facilitate hanging them in the frame. When tested, only the mortars were temperature conditioned. The shells were at or close to the ambient temperature. The mortars were placed in an insulated container and liquid carbon dioxide was used as the cooling medium.

It will be noticed that tests were performed at several temperatures about the two nominal temperatures of -20°C and 20°C. Normally, the mortars were cooled to 5°C lower than those temperatures indicated in the video, photographs and debris distribution graphs. This was to compensate for the heat gain during the time taken to hang, charge the mortar and function the shell. The nominal 20°C tests were normally performed at the ambient temperature. All the reported temperatures were rounded to the nearest 5°C.

Several tests were performed at extremely low temperatures to determine the limits of some of the mortars, especially steel. Tests to determine the effect of higher temperatures were also performed in the summer on some of the plastic mortars by leaving them to warm in the sun.

A shell was prepared by removing and placing the lift charge in a small plastic bag. An electric match was taped to the delay element, the shell was lowered in the mortar and the lift charge dropped on top of the shell. The mortar was now ready to hang in the frame.

DATA TREATMENT

Once the shell was functioned, the area was thoroughly searched for mortar and plug fragments. Except for the very small ones, the pieces were marked with the distance value from the origin. Although an attempt was made to recover at least 90% of the initial mass, it was sometimes impossible.

The mortar pieces were photographed and weighed. Debris distribution plots, such as the one shown in Fig. 3, were then generated with the number of mortar and plug pieces and mortar and plug mass as a function of distance.

When many small pieces (mass less than 1 g) were found, as with the fibre reinforced mortars, they were weighed together. A debris distribution graph where this occurred will show very many pieces but little mass.

SAFETY CRITERIA

Although, a full scale examination of the lethality of each mortar/plug fragment is beyond the scope of this report, it is necessary to establish tentative criteria by which the level of hazard from a bursting mortar can be quantified. The assumptions, for this preliminary examination will be that;

a) a mortar bursting in many pieces is more dangerous than one that bursts in few pieces,
b) pieces that are thrown long distances are more dangerous than those thrown short distances,
c) plug pieces are more dangerous than mortar pieces.

The probability to injure must be considered within the area (more correctly, volume), where an incident may occur. In a typical fireworks display, fewer people are within the "operator zone" than in the "spectator zone". Then, again, the probability of finding a higher concentration of and higher energy fragments is greater at close range, in the "operator zone", than in the "spectator zone". Thus, the three assumptions do not unduly bias either the operator or spectator.

In general, it is assumed that the probability of an injury occurring would be higher, the higher the number of fragments and the greater the distance that they travel. This may seem to bias the presence of spectators but in fact, the probability of striking and injuring an operator is very high due to the higher concentration and speed of the fragments close to the source. It can be argued that those fragments that are thrown long distances are projected at large elevation angles and may not pose a danger to the operator. Different scenarios will arise when the mortars are buried, placed in racks and/or the shells are fired electrically. Also, without considering the mass of the fragments and their respective energy, the degree of injury cannot be assessed.

The last assumption which states that the plug pieces are more dangerous than the mortar pieces has been made to balance the effect from the low density mortars (paper) and from the fact that the plugs often carry the fasteners with them. This assumption would be more relevant for rack mounted mortars.

OBSERVATIONS

Many mortars were submitted for evaluation under this program. Initial observations indicated that the majority were well constructed but some did have flaws. Some details of the mortars, mortar material properties and the test shells are given in Appendices A, B and C.

Mortar Plugs and Fasteners

Basically two types of plugs were observed to be used. Some were manufactured from either one piece or laminated pieces of wood with the grain parallel to the mortar. These plugs were normally well made because they were turned to the proper diameter on a lathe or similar equipment.

The other type of plug was assembled by nailing nominal 5 cm thick planks together to obtain the required thickness. The grain of each piece would be oriented perpendicular to the grain of the adjacent piece. Most of these plugs were in poor shape. Many were out-of-round, cracked or had pieces missing. This resulted in gaps between the plug and mortar.

The plugs were installed with either steel staples, nails (spiral or roofing) or a combination of both or with screws. In none of these methods were attempts made to strengthen the assembly by increasing the fasteners' bearing surface (i.e. use of washers) or were the number of fasteners or their position consistent within each type of mortar.

Other observations on all plugs included poor installation, one batch with only one nail and another with no nails at all. Many of the nails were either not or poorly seated against the mortar wall.

Paper - Plain - Convolute Wound Mortars (Paper-P-S)

The plain, non-impregnated, convolute wound mortars were found to be in poor condition. Although new, the paper layers could already be seen separating at the mortar ends. The 76 mm size had the plug with the grain oriented parallel to the tube while the 102 and 127 mm sizes had plugs with the grain perpendicular to the tube. All the plugs were fastened with four nails. These mortars of Spanish origin had metric sizes printed on the mortar wall.

As a result of poor adhesion between layers, when a mortar burst, many of the fragments would result from the paper layers separating. See Fig. 4.

Normally, a star shell caused the plug to be simply blown out, with the larger shells also causing the mortar to burst. The maximum number of fragments produced was approximately 48 and the larger pieces were thrown to 55 m.

Report shells caused all the mortars to burst in many pieces. The 76 mm shell fragmented almost every plug, whereas, the 127 mm shell normally blew the plug out whole or split it in two. Plug pieces were all found within 15 m. The maximum number of fragments was 120 and they were found as far as 75 m.

An interesting occurrence is that of Test #10, where, the ignition of the report shell caused the mortar hanging system to break and the shell to burst in the mortar as it lay on the ground. The mortar burst producing approximately 30 fragments which were thrown to a distance of 30 m. The plug remained intact and was thrown to a distance of 85 m.

Paper - Impregnated - Spiral Wound Mortars (Paper-I-S)

The few impregnated, spiral wound mortars supplied, were in very good shape. The ends did not show any sign of the paper layers separating or unravelling. The plugs of the 76 mm size had the grain oriented parallel to the mortar and were fastened with staples while those of the 102 mm had the grain perpendicular to the tube and were fastened with staples and roofing nails.

Figure 5 shows that when these mortars burst, the paper layers did not tend to separate as much as the not impregnated paper mortars.

Out of the seven tests with star shells, only one mortar burst. In the remainder, the plug was either simply blown out in one piece or split in very few pieces. The one 102 mm mortar that did burst, produced approximately 45 fragments that were thrown to a distance of 45 m.

Tests with report shells were only performed on 76 mm mortars. All the mortars burst and the plugs, with the exception of one, were fragmented. The maximum number of pieces produced was approximately 60 and they were thrown to a maximum distance of 35 m.

Paper - Impregnated - Convolute Wound Mortars (Paper-I-C)

The impregnated, convolute wound mortars were well made. The plugs were nailed and had the grain parallel to the mortar. An epoxy seal/adhesive was also used on the inside surface of the plug and between the plug and mortar resulting in no gaps and a good finish. Very few of these mortars were supplied and in only two sizes, 102 and 127 mm.

Although the supplier stated that these were impregnated paper mortars, it is suspected that they were not. Witness from Fig. 6, how cleanly the layers can be seen to have separated when the mortar burst.

In all the trials with the star shells, the plug was blown out in one piece and only the 127 mm mortars burst. The 102 mm tubes remained intact. The maximum number of fragments produced was approximately 45 and were thrown to 45 m.

In both trials with report shells, the 127 mm mortars burst and in one, the plug fractured into 15 pieces. Approximately 20 fragments were produced in each trial and were found to a distance of 25 m.

High Density Polyethylene (HDPE) Mortars With Plug

The plugged HDPE mortars were not very well made. The ends were cut neither squarely nor cleanly and as a result some could not be stood on end. This can be seen from Fig. 6. An observation made on HDPE mortars is that there always seems to be some shrinkage where it is cut. As a result, the diameter of the mouth of a mortar is always reduced. Two firms submitted HDPE mortars with wooden plugs.

Sample 1

Sample 1, was available in 76, 102, 127, and 155 mm sizes. Most of the plugs were manufactured with the grain oriented perpendicular to the mortar and were fastened with staples. Very few of the plugs survived. The plugs were blown out in all the tests, with some fracturing to as many as 20 fragments when tested with a report shell.

From the 19 trials with star shells, none of the 76 mm mortars burst, one 102 mm split (See Fig. 8) and four 127 mm split at several places. In the case of the 155 mm, the mortars either sustained long splits or severe mangling in the typical stretched fashion. The latter effect can be seen in Fig. 9. The maximum number of fragments in these tests was 20 and resulted mostly from the plug splitting. The fragments were found to a distance of 45 m.

The report shells caused all the mortars to burst and the plugs to split. The number of fragments ranged from approximately 15 to 30 and were found to distances of approximately 45 m. Figure 10 shows the interesting results from a test performed at -35°C. The brittle fragments produced numbered approximately 160 and were found to a maximum distance of 55 m.

Several tests in this series displayed the typical fold-back that has often been encountered by others who have tested HDPE pipe. The pipe experiences forces that cause the burst end to turn inside out.

Sample 2

Sample 2 was available in only two sizes 127 and 155 mm. The single piece, soft wood, plugs were fastened with nails and had the grain oriented parallel to the mortar, however, the wood seemed to be in poor shape. Some plugs were cracked and had shrunk away from the mortar wall resulting in gaps.

Out of the eight tests with star shells, one plug was shattered into 27 fragments, and one survived. In the remainder of the tests, the plugs split into two to six pieces. The report shells seem to have done less damage to the plugs. Out of the five tests, two plugs survived and the other three were split producing three to six pieces. All the plugs and plug pieces were recovered within a 5 m radius.

In the low temperature tests, the following results were obtained with star shells. One tube survived, one suffered splitting near the bottom end, and the other split into three pieces that were recovered at a maximum distance of 35 m. At the higher temperature three of the mortars were split as in the low temperature tests whereas, the other two suffered extensive stretching and mangling.

The damage from the report shells was more extensive. In the five tests all the mortars burst, producing from 2 to 24 fragments that were thrown to a maximum distance of 45 m. Two of these tests displayed the typical fold-back.

High Density Polyethylene (HDPE), Moulded Mortars

This is one of the newest mortar designs on the market. The blow mould fabrication process results in a very consistent product with the wall thickness increasing toward the bottom. Figure 11 shows one of these mortars.

The moulded HDPE mortars are approximately 50% lighter then their plugged counterpart. Only 76 and 102 mm sizes were available at the time of testing. Although there are plans, the blow-mould process does not readily lend itself to manufacture such mortars in larger sizes.

The star shells caused all the 102 mm mortars to split open over a short distance in the bottom area. Smaller splits or bulges were produced in the 76 mm mortars. As indicated by Fig. 12, none of the damage was accompanied by any fragments. One mortar that was warmed in the sun to 40°C suffered no damage.

The report shells caused all the mortars to burst. All of the pieces indicated that stretching occurred before breaking. The number of fragments varied from about 10 to 25 and were thrown to a maximum distance of 45 m. The one mortar tested at 40°C did not show any discrepancy in the number of fragments produced except that they seemed to be stretched longer.

Acrylonitrile-Butadiene-Styrene (ABS) Mortars (ABS1)

These mortars will be referred to as ABS1 to simplify discussion in this report. The ABS1 mortars had the ends cleaner cut than the HDPE. All plugs had the grain oriented parallel to the mortar. Most of the plugs were nailed except for a few of the larger diameter ones that were screwed to the mortar.

Since most ABS mortars are being replaced with HDPE, only two sizes, 76 and 102 mm, were available from fireworks operators for evaluation. Out of the 14 tests, 50% of the plugs survived intact, five split to a maximum of five pieces, and the remaining two split into 13 pieces.

At the low temperatures, star shells caused both the 76 and the 102 mm mortars to burst. All the plugs survived. The mortars fractured producing from 16 to 54 pieces that were thrown to a maximum distance of 45 m. As described by other researchers, there was no evidence of stretching on the fragments formed. The pieces had brittle fracture characteristics, being cleanly broken and sharp edged. In the 20°C tests with the star shells, the plugs were either blown out whole or split to a maximum of five pieces, with the mortar tube surviving all the tests. The pieces were thrown a maximum distance of 15 m.

The report shells caused all the mortars to burst and although, a couple of plugs survived intact, these shells were also responsible for causing the plugs to split into the maximum number of pieces. The cold temperature tests produced the most mortar fragments (maximum 90) that were thrown to distances of approximately 70 m.

Acrylonitrile-Butadiene-Styrene (ABS)+Hardwood Plug Mortars (ABS2)

These mortars (denoted as ABS2) were manufactured at CERL to determine if there was any noticeable effect when plugs were manufactured from laminated hardwood, were close-fitting and the grain oriented parallel to the mortar. The plugs were made longer than normal to provide sufficient surface for the fasteners. This resulted in a mortar having a rigidly fastened plug. They were installed with two rows of screws countersunk into the plastic. These mortars were manufactured in three sizes, 76, 102 and 155 mm.

The plug was blown out intact in seven out of the eleven tests. In the remaining four tests, the mortars survived intact.

In the low temperature tests with the star shells, only the 155 mm mortar burst producing 14 large fragments that were thrown a distance of 75 m. The 76 and 102 mm mortars survived intact. From the three tests performed with star shells at 20°C, including those on mortars that were sun-warmed, two mortars burst producing a maximum of 12 large fragments. They were found to a maximum distance of 55 m.

From the limited number of tests with report shells, there seems to be very little difference between those performed at the high and low temperatures. The mortars all burst, producing from 18 to 28 pieces that were thrown to a distance of 75 m. The sun-warmed mortar burst into 14 pieces.

Fibre Reinforced Epoxy (FRE) Mortars

The tube used to manufacture the fibre reinforced epoxy mortars is commercially available as electrical conduit for above and below ground use. These mortars were generally well constructed except that the number of fasteners varied from 0 (loose plug) to 1, 2, 3, 4, and 8 per mortar. The plugs of all sizes except the 155 mm had the grain oriented parallel to the mortar. Because the manufacturer was experimenting with the 155 mm size, nominal 5 cm thick, stacked lumber was used to make plugs for these mortars. Many of the plugs were manufactured from wood that was in poor condition. Any defect with the plugs was made evident by the nearly perfect roundness of the FRE pipe. These mortars were supplied in 76, 102, 127, and 155 mm sizes.

Most of the plugs of the FRE mortars survived the tests with the star shells. Out of the 18 tests, 8 plugs remained intact, 2 split in two and the other 8 fragmented from 12 to about 70 pieces. These all landed within 5 m of the origin. Only one plug survived the report shell tests. The others fragmented producing from 3 to 30 pieces, all landing within 25 m of the origin.

There does not seem to be any distinction between the tests performed with star shells at low and high temperatures. In both cases, none of the mortars burst. In the tests with the 76 and 102 mm sizes, the plug was simply blown out whole or split in two. With the 127 (See Fig. 13) and 155 mm sizes, although the tube survived, the plug was fragmented to as many as 70 pieces. As a result, the mortar was usually left hanging in the test frame and only plug pieces were thrown to a maximum distance of 15 m.

Every mortar was burst by the report shells as shown in Figures 14 and 15. The effect of the blast was very localized and there was no sign of crack propagation. Due to the many small pieces produced, the mass recovery, although fairly consistent, was never very high. It ranged from 78% to 85%. The number of mortar fragments recovered varied from 20 to approximately 130 and were found to distances of 35 m.

Aluminum Conduit Mortars

The aluminum conduit mortars were assembled with plugs which had the grain oriented parallel to the tube. Again, due to the near perfect roundness of the conduit, any defects in the plugs tended to leave gaps. The plugs were fastened with T-shaped nails to the conduit. These mortars were supplied in 76, 102, 127, and 155 mm sizes. Although well made, the inside diameter was often found to be too small. Even with the wrapper removed, some shells had to be forced into the mortar. This problem became such a safety concern that testing of these mortars had to be suspended.

In general, when the burst was caused by report shells, the fractures were often of a brittle nature. Away from the centre of the burst location, the aluminum showed signs of elongation. A similar effect was noted in the tests with star shells.

Out of the 18 tests, in only one did the plug remain fastened to the mortar. In the others, the plug was either blown out intact (8 tests), split into 2 to 7 pieces (6 tests), or fragmented up to 33 pieces. Plugs or plug pieces were found to a maximum distance of 20 m.

In the tests with the star shells, the trend was towards more damage as the size increased. Except for the plugs being blown out, the 76 mm mortar tubes all survived. Also, one out of the three 102 mm, two out of the three 127 mm (See Fig. 16) and all the 155 mm burst. The number of mortar pieces ranged from 2 to 17, with most being found within 80 m except for two which were thrown approximately 125 m from the source.

The report shells caused all the mortars to burst, producing much smaller and more numerous fragments than those in the star shell tests. Compare Fig. 16 to Fig. 17. The damage sustained by the 76 and 127 mm sizes was very similar, with the number of fragments ranging from 12 to 29 and being thrown to maximum distances of 80 m.

Sheet Steel Mortars

Again, as a result of the manufacturing process, the sheet steel mortars with integral convex bottom were very well made and of consistent quality. Bottom, seam and collar band were all spot welded. The painted mortars were received in individual cardboard boxes. They were the only mortars identified by size and colour-coded labels that also included instructions on use. These mortars were supplied in 76, 102, 127, and 155 mm sizes.

The sheet steel mortars behaved in a similar fashion to the aluminum except that they burst into larger and fewer pieces. The spot-welded plugs were either left intact in the mortar or blown out and bent. In a test with a report shell, a plug was blown out and also punctured.

Tested with star shells, all the 76 mm mortars survived as indicated in Fig. 18. The 102 mm sizes also survived the high temperature tests but in two of the three low temperature tests, the plug was blown out of the tube. At both temperatures, the 127 (See Fig. 19) and 155 mm mortars burst. The number of pieces recovered ranged from 3 to 10 pieces with most being found within a 75 m radius. However, two pieces were found beyond this range; one at 90 m and the other at 113 m.

The report shells caused both the 76 and 127 mm mortars to burst. The tests performed at lower temperatures produced the most fragments as did the larger size shell. The number of fragments produced with the 76 mm mortars ranged from 3 to 13 and were found to a distance of 55 m. Tests on the 127 mm mortars (See Fig. 20) produced from 12 to 20 fragments that were thrown to a maximum distance of 85 m. These maximum distances for the fragments were quite reproducible for both shell sizes.

Schedule-40 Steel Mortars

The schedule-40 steel mortars were specifically made for these tests. In the initial trials, the bottoms were butt-welded to the ends of the pipe. Due to the results obtained in the preliminary tests, the design was later modified. The bottoms were welded a short distance from the end and inside the pipe. These mortars were manufactured in 76, 102, 127, and 155 mm sizes.

The results from the Schedule-40 steel mortars indicated that the star shells were not sufficiently energetic to cause any of them to burst. Also testing a 155 mm mortar three times at very low temperatures did not result in any damage. Only at sufficiently low temperatures, did the 127 mm report shells cause the mortar wall to crack (See Fig. 21) and only under repeated firings at -35°C, did one eventually burst (See Fig. 22) producing one fragment that was thrown a distance of approximately 65 m.

DISCUSSION OF RESULTS

Table 1 shows the tests performed and provides an indication of the extent of damage sustained by the mortars. A multitude of conclusions can be derived by comparing the volume of photographs and/or viewing the video records (1). As examples, one can easily notice differences in the damage caused by star shells versus that of report shells or the effect of temperature on the type of fracture or fragment sizes. It will also be noted that the 102 mm star shell is the critical size at which mortars begin to sustain substantial damage. In most materials, the 127 mm and 155 mm shells cause the mortars to burst. This undoubtedly relates to the amount of composition in the shells.

In this section, some advantages and disadvantages of the various mortar materials and assembly methods will be discussed. Again, the discussion will often be from the point of view that a well fastened plug is desirable.

Mortar Plugs and Fasteners

This topic initially comprised part of reference (1) but has since been published separately, in part, as reference (7). Due to the narrower scope of this presentation, this topic will not be discussed in detail.

In general, the use of a plug introduces at least two dissimilar materials in the manufacture of a mortar. One begins with a mortar tube, say paper, adds a wooden plug and fastens it with metal nails, screws or staples. Additionally, an adhesive could also be used. Due to the dissimilar thermal and mechanical properties of these materials, one must take care in the assembly process. Ideally, the components must work together to maintain a minimum required strength. Thus, the wood, and paper tube in this case, should not swell or shrink with humidity and temperature (including freezing and thawing) so as to work against the fasteners and each other. Above these often uncontrollable factors, are the forces experienced by a mortar during use.

It is difficult to maintain a rigid construction with a mix of component materials. Possibly, from the above point of view, the worst mix is a wooden plug with a metal or plastic tube. Metal is a good conductor relative to wood and it can quickly follow temperature fluctuations resulting in expansion or contraction that could result in the eventual loosening of fasteners.

As experienced by many, plastic mortars can attain very high temperatures when left in the direct rays of the sun. This could also lead to working against the plug fasteners.

With either type of plug, it is important to have an appropriate thickness so that the assembly will increase the overall strength rather than weaken it. Plugs designed with the grain oriented perpendicular to the tube have some inherent disadvantages. The discs cut from planks will normally have one or two segments with short grain lengths that often result in breakage either during the curing or assembly process. It is possible to negate this shortcoming during assembly, by stacking discs so that the grain of each piece is oriented at right angle to the adjacent pieces. As already mentioned, the discs are usually nailed together with no adhesive. Thus, the effective thickness for fastening the plug to the tube remains the thickness of the individual planks. When assembling the mortar, the fasteners should be driven radially into the plug at the centre of every disc and perpendicular to the grain. This will prevent damaging the discs, will provide the strongest bond and will naturally stagger the fasteners around the mortar tube. To avoid splitting, care must be taken that not too many fasteners are driven onto the same plane.

The resistance of withdrawal (7,8,9) of fasteners from wood, not only depends on the type of fastener and wood but also on the orientation of the fasteners relative to the grain of the wood. All of these parameters can be controlled by the manufacturer. Economics, of course, does enter the picture.

Fasteners used in the assembly of mortars are subjected to lateral and withdrawal loads when in use. That is, if a force is applied along the axis of the mortar, (as by a piston) to bear only on the plug, the fasteners would experience a lateral load. Then, if the tube and plug material were of higher strength (and not easily deformed) than the fasteners, the fasteners would shear and the plug would be pushed out. However, since the plug is made of wood and since most mortar tubes are made of soft materials, they will normally experience some deformation. This deformation may result in the fasteners bending and giving rise to withdrawal loads.

The fast, high pressure transients produced by the lift charge causes the tube to experience a deformation that "simultaneously" loads the fasteners laterally and in withdrawal. These repeated loads may, eventually, cause loosening of the fasteners.

Paper Mortars

Paper tubes have become attractive as mortar material due to their competitive costs. However, more than any other, paper mortars require frequent judgements as to whether to continue their use. These inspections are necessary since paper can be damaged by water, by unravelling, by heat and by flame. The mass between the various types of paper mortars varied considerably not only because of the plugs used and the difference in length, but also due to their different densities. Their specific gravity was determined to be 0.75 for the plain convolute, 0.85 for the impregnated spiral and 0.80 for the "impregnated" convolute.

On the basis of the maximum distance to which fragments were thrown, the plain, convolute wound mortars were the worst performers. Fragments were recovered to distances of 75 m, whereas, fragments for the other two types of paper mortars were thrown only to maximum distances of 45 m. This is mainly due to the plain, convolute wound mortars having metric dimensions which results in a tighter fit and not so much on its construcotion. This increased confinement resulted not only in fragments being thrown farther but also in the production of many more and smaller fragments. The difference between Figures 23 and 24.

The video and high speed film records indicate that normally, the star shells simply blew the plugs out, causing flames to jet out of both ends and not damaging the tube. The larger star shells and report shells caused the mortars to burst with the star shells generally producing the larger mortar fragments. A spherical fireball accompanied this type of rupture.

Plastic Mortars

Many tests have been performed in Australia, Britain and the United States comparing PVC, ABS and HDPE. PVC has been abandoned as a mortar material and ABS is following the same fate. HDPE is now the most common plastic for the manufacture of mortars.

Some differences were found in the results between the series of tests on ABS1 and ABS2. None of the ABS1 mortars survived intact. In seven of the tests with star shells the tubes survived but the plug was blown out. The report shells burst (See Fig. 25) all the mortars. Only seven of the plugs survived intact.

In the tests with star shells on the ABS2 mortars all but one burst in the 76 and 102 mm sizes. The 155 mm (available only as ABS2) mortars tested with star shells and all mortars tested with report shells (See Fig. 26) also burst.

In general, many more and smaller fragments were produced with the ABS1 than the ABS2 mortars. The distribution of, and the maximum distance to which fragments were thrown was approximately the same for both types of ABS mortars.

HDPE is easy to work with. It normally has a substantial wall thickness that allows for rigid fastening of a plug. Care must be taken with this material since it has a tendency to shrink in the area where it is cut. The shrinking also seems to increase with use in the mouth region. Therefore, one must monitor the mouth of the mortar and make sure that it does not shrink to a dangerous level. Operators have also reported that shrinkage due to low temperatures (-30°C) often causes problems when loading some shells.

Tests were performed on 102 mm moulded and plugged HDPE mortars using a heat gun. Temperatures were monitored on the surface of the HDPE and half-way through its thickness. Heat was applied until the surface temperature reached approximately 130°C. The temperature in the HDPE was normally 25°C lower. The mortar was then allowed to cool and the diameter of the mortar was measured. This cycle was repeated four or five times for eight mortar samples. The changes in diameter were very similar for both mortars. The maximum decrease in the inside diameter was 2.8 mm. It was possible to cause a larger change in the dimensions but this was normally accompanied by distortion and collapse of the mortar wall. This is very unlikely to occur during normal use.

In general, the results for the HDPE mortars indicate that the smaller star shells blew the plug out (See Fig. 27) but large star shells and all report shells burst the mortar. The typical foldback of HDPE pipe as reported by others was displayed in several of the test results. Also, in HDPE, the transition point from brittle to ductile fracture seems to occur close to -35°C as indicated by the results of Test 240. The results indicate that the failure mode of HDPE mortars is much more acceptable than that of ABS.

A comparison made of the 76 and 102 mm mortar sizes that were common to both the plugged and the moulded HDPE mortars indicates the following results. Out of nine tests with star shells on the plugged mortars, only one burst and the plugs were blown out of the rest. All plugs and plug fragments were recovered within a 5 m radius. In the ten tests on the moulded mortars, 50% survived whereas the remainder suffered a small split with no associated fragments.

When making comparisons between these two types of mortars it must be remembered that the mass of the plugged mortar is approximately twice that of the moulded. In the tests with the report shells, comparisons can only be made with the 76 mm size. With the plugged mortar, (Fig. 28) the plug was either blown out intact or in pieces. The maximum number of fragments produced numbered 25 and were found to a maximum distance of 45 m. The report shell caused the bottoms of the moulded mortars (Fig. 29) to burst producing a maximum of 25 fragments that were found within a radius of 45 m. Taking the mass in consideration, the performance of the moulded mortars is deemed superior.

Fibre Reinforced Epoxy (FRE) Mortars

When adjusted for the length, the fibre reinforced epoxy mortars were the lightest tested. Its specific gravity is 1.94. Although the tube material looks brittle, it can sustain substantial deformation before cracking. It also has good shock absorbing properties. The FRE material is impervious to moisture over its surface, however, once cut, the fibres are exposed and moisture can penetrate through capillary action. This would not normally be a problem unless the moisture is allowed to freeze. Then fibre separation could lead to failure. FRE specifications (11) indicate that the water absorption according to ASTM D570-59 is 0.113% at room temperature over a 72 hour period. Corrective action, however, can be taken with an appropriate sealing compound such as epoxy.

A concern that arises in the manufacture of mortars with this material is with regard to its thin wall and the possibility of damaging it. It would be more effective and less damaging to use a washer with either ringed nails or screws to fasten the plug. To further reduce damage and increase the integrity of the assembly, the plug should be round and well seasoned before installation.

Based on the distance that the fragments were thrown, and the fact that none of the tubes tested with star shells burst, this mortar was the best performer. The mortar normally shredded into small pieces composed of a few strands of fibre. The larger pieces were surrounded by loose fibres resulting in fragments with poor aerodynamics and as a result were not thrown far.

Metal Mortars

The metal mortars tested were comprised of those manufactured from aluminum, sheet steel and Schedule-40 steel pipe. As indicated in Appendix A, the aluminum and sheet steel mortars were of approximately the same mass whereas that of the Schedule-40 steel mortars was seven times greater.

The advantage of aluminum for producing light-weight mortars was lost with the use of the wooden plug. Through the use of a welded aluminum plate, the mass could be greatly reduced but this would substantially increase the cost. As already mentioned, some of these mortars were not sized correctly. Proper sizes are available in the Schedule-40 pipe series but again these are more expensive and would more than double the mass of aluminum. The aluminum conduit used had a fairly thin wall. This requires some precautions when the plug is installed and would benefit from the use of washers to increase the load bearing area.

The high thermal conductivity value of aluminum (relative to wood), means that it can quickly follow temperature variations. That is, if a mortar is placed in the sun, its temperature will quickly rise whereas that of the plug will lag. The temperature rise will cause the aluminum to expand faster and more than the wood (assuming dry wood). As explained earlier, this will result in withdrawal loads against the fasteners that may eventually cause the plug to loosen.

Tests have indicated that both star and report shells burst these mortars with the report shell producing the smaller and more numerous sharp-edged fragments. As already stated, the majority of the fragments were found within 85 m except for one that was thrown to a distance of 125 m.

Sheet steel mortars were among the lightest tested. No problems are encountered with dissimilar materials in this design due to the "integral" plug. Again, the manufacturing process results in a product of consistent quality. Most of the 76 and 102 mm mortars survived the tests with star shells but the larger sizes and those tested with report shells suffered considerable damage. The majority of the fragments were found within 75 m except for a few that between 75 and 115 m.

Steel pipe mortars have been in use for many years. Due to steel's strength and availability it was easily accepted as mortar material. Based only on the number of mortars that burst, Schedule-40 steel mortars would be deemed the best. It must be kept in mind that in the Preliminary Tests, the butt-welded bottoms were often blown off. This led to a re-design. The plug plate diameter was machined to the inside diameter of the pipe, inserted a depth equal to the plate into the pipe and continuously welded on the perimeter.

Mortars suffered damage only with report shells and then, some only at low temperatures and/or after multiple testing. Why were so few mortars damaged in the tests? In use, bursts are reported regularly. It has been suggested that the shells used in the tests were not the most powerful. It must be stated, however, that the Schedule-40 steel mortars made at CERL were manufactured from new steel pipe and welded by a licensed welder. The same cannot be said about other steel mortars in use. One cannot assume that all pipes and tubes are commercially manufactured and as such, are welded or fused to some standard by a licensed welder.

Observations made on many steel mortars in use by various operators revealed that the inside surface of the pipes was often very rough. Some seemed to have the graininess of cast iron. This could be caused by the corrosive action of the combustion products of the lift charge. However, it has also been admitted that used pipe is often purchased to manufacture mortars. This practice should be avoided since it is difficult to determine the type of steel or the working environment (chemical or temperature cycling) that it has been subjected to. The type should be known to avoid easily hardenable steels and to ensure proper welding. Since resistance to impact depends on the ductility (13), steels with a high modulus of toughness should be selected.

Other effects that may lead to a steel pipe failing (i.e. a mortar bursting) include fatigue and surface modification. Fatigue refers to a repeated-load phenomena such as would occur on the crankshaft of an engine. Although the frequency of loading is much lower in mortars than that which would be encountered in the crankshaft example, the loading is accompanied by other phenomena as described below. Generally, the number of repeated loadings to cause failure depends on the magnitude of the load. Failure by fatigue is due to progressive cracking which eventually leads to catastrophic (i.e. brittle) fracture. Fatigue cracks start at a point of maximum stress at a point of stress concentration referred to as a stress raiser. Stress raiser are found within the metal as voids or inclusions of foreign matter and on the surface of the metal as rust pits, scratches, etc. In failures caused by fatigue, the initiation point can usually be determined.

Also, progression of the crack will cause the appearance of rings radiating from the point of origin.

The other effect that is being considered that may cause hardening and premature failure is that of surface modification of steel, by chemical adjustments, through repeated use. In the presence of gaseous carbon compounds and heat and pressure, carburization can occur. Carburizing is the process by which carbon is introduced into a solid, iron-base alloy (steel) by heating above the transition temperature while in contact with a carbonaceous material. On ignition of the lift charge, carbon compounds, high temperatures and pressures are all present, although for a short period of time. Refer to Fig 30. Carbon increases the hardness of steel and in the case of a steel mortar, the result may be a pipe having a hard (brittle) internal surface and a tough exterior. This topic remains to be investigated.

SUMMARY

The results do not indicate serious faults with any particular mortar material. It is easy to note the difference in the damage (See Figures 31 and 32) caused by star shells versus that of report shells. The low temperature tests indicate that there is an effect on the type of fracture and fragment size (See Figures 33 and 34). Differences can be noted from Figures 35, 36, 37, 38, and 39 which show the effect of the same shell on various mortar materials. It was also found that 102 mm is the critical size of a star shell at which mortars begin to sustain substantial damage. This effect can be seen from Figures 39 and 40 for aluminum mortars.

Except for the Schedule-40 steel which burst only at very low temperatures, all other mortars ruptured and produced fragments under most conditions. Safety criteria can then be based on the number and mass of the fragments produced and the distance to which the fragments were thrown. The fragments from the fibre reinforced epoxy mortars had a range of approximately 30 m, the paper 70 m, the plastics 70 m and the metal mortars 120 m. The lethality of these fragments and the blast overpressures were not considered here but will be the topic of a future report. Also, the debris distribution data is being condensed for the various mortar materials to provide a better overview of the danger posed by the fragments to operators and spectators.

The data generated from this study can and will be used as a guide to develop mortar standards and improve the construction of existing mortars and possibly lead to new designs.

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Table 1 - Mortar evaluation results

Mortar Type	Star Shells								Report Shells			
	Temperature -20°C				Temperature 20°C				Temp -20°C		Temp 20°C	
	Sizes/mm				Sizes/mm				Sizes/mm		Sizes/mm	
	76	102	127	155	76	102	127	155	76	127	76	127
Paper												
-Plain, Conv	ppb	pp	bb	N/A	pp	b	bbb	N/A	BBb	BBBB	bbb	BBB
-Impreg, Spir	N/A	PPb	N/A	N/A	pP	pP	N/A	N/A	BBB	N/A	BbB	N/A
-Impreg, Conv	N/A	pp	bbb	N/A	N/A	ppp	N/A	N/A	N/A	Bb	N/A	N/A
HDPE												
-Plug-Sample 1	PPP	Pp	PP	bB	Pp	PB	PBB	BBB	Bb	BBB	BBB	BBB
-Sample 2	N/A	N/A	P	BB	N/A	N/A	BB	bBB	N/A	bB	N/A	BbB
-Moulded	SSS	bb	N/A	N/A	SS	bbS	N/A	N/A	bbb	N/A	bbb	N/A
ABS												
-Regular	bb	b	N/A	N/A	pp	PPP	N/A	N/A	bBB	N/A	BbB	N/A
-Hardwood Plug	SS	S	N/A	b	N/A	Sb	N/A	b	b	N/A	bbb	N/A
Fibre	pp	ppp	PPP	P	pP	Ppp	PPP	P	BBB	BB	BBB	bBBB
Aluminum	p	p	b	B	S	pB	PB	BB	b	N/A	bbb	BBB
Steel												
-Sheet steel	SSS	Spp	bbb	bbb	SS	SSS	bbb	bbb	bbb	bbb	bbb	bbb
-Sched-40 pipe	SS	S	S	SSSS	S	SS	SS	SS	SS	bSbSb	SSS	SSb

S - Mortar survived
p - Plug blown out intact but tube survived
P - Plug blown out and fragmented but tube survived
b - Mortar burst but plug remained intact
B - Mortar burst and plug fragmented

APPENDIX A - Mortar Specifications

Mortar Material	Size /mm	Mass /g	Inside Diameter /mm	Wall Thickness /mm	Inside Length /cm	Plug Length /cm
Paper-P-S	76	430	72	5.2	36.3	3.5
	102	1770	99	10.2	55.2	4.8
	127	3400	123	12.4	71.9	5.7
Paper-I-S	76	1190	76	10.2	52.1	4.4
	102	2680	101	12.9	65.4	5.7
Paper-I-C	102	2160	103	10.7	52.1	10.8
	127	3960	128	12.7	72.7	13.0
HDPE+Plug (Sample 1)	76	1260	77	6.4	73.3	3.5
	102	1720	102	6.4	68.6	7.9
	127	2720	125	7.8	68.9	8.0
	155	4730	159	8.7	79.5	11.9
HDPE+Plug* (Sample 2)	127	3020	126	6.9	74.2	9.5
	155	4210	152	7.3	81.0	9.8
HDPE-Mould#	76	590	80	4.3	46.5	0.7
	102	1280	104	6.2	61.0	0.9
ABS	76	950	77	5.3	46.5	5.2
	102	1890	102	5.2	66.0	6.5
ABS-RDwood	76	1320	77	5.7	40.6	11.4
	102	2450	102	6.5	53.3	15.2
	155	6210	153	7.6	61.0	22.9
Fibre	76	470	76	1.6	48.3	5.0
	102	810	103	1.6	54.0	6.9
	127	1430	127	2.4	53.0	7.9
	155	2530	152	2.5	83.0	8.1
Aluminum	76	530	73	1.3	40.2	6.0
	102	1500	97	2.2	70.8	5.4
	127	2110	123	2.1	68.9	7.3
	155	2690	148	2.3	68.3	7.8
Sheet Steel	76	970	76	0.8	46.6	0.8
	102	1560	102	0.8	53.3	1.5
	127	1960	127	0.8	52.1	1.5
	155	2520	151	0.8	57.8	1.5
Steel Sched-40	76	6700	76	5.5	50.8	1.3
	102	10400	102	6.0	55.9	1.3
	127	14700	128	6.6	54.9	1.3
	155	20800	154	7.1	60.3	1.3

#See manufacturer's specification sheet for detail dimensions.

APPENDIX B - Shell Specifications

Shell Type	Shell Shape	Size /mm	Lift Charge Mass/g	Composition Mass/g
Star	Cylindrical	76	28	142
	Spherical	102	57	138
	Spherical	127	85	236
	Spherical	155	113	771
Report	Cylindrical	76	28	43
	Cylindrical	127	71	99

APPENDIX C - Mortar Material Properties

Thermal coefficient of linear expansion

Wood (Note that for wood, thermal expansion is often overshadowed by the larger dimensional changes due to moisture content.)

Longitudinal grain - 3.4 X 10^{-6}/°C (Independent of specific gravity)
Across grain radial - 25.7 X 10^{-6}/°C (Specific gravity of 0.46)
Across grain tangential - 34.8 X 10^{-6}/°C (Specific gravity of 0.46)

Paper - N/A
HDPE - 15 to 30 X 10^{-5}/°C
ABS - 8.5 X 10^{-5}/°C
PVC - 5.0 to 14.8 X 10^{-5}/°C
Fibre (Resin) - 2.2 X 10^{-5}/°C
Steel - 1.4 X 10^{-5}/°C
Aluminum - 2.4 X 10^{-5}/°C

Thermal conductivity in W/m °C

Wood - 0.059 to 0.171 (Heat flow across grain in Balsa to Red Oak. Heat flow parallel to the grain is 2 to 3 times higher.)
Insulating fibreboards - 0.045
HDPE - 0.33
ABS - 0.14 to 0.21
PVC - 0.12 to 0.17
Fibre - 0.29
Steel - 35 to 70
Aluminum - 225

Specific gravity

Wood - 0.16 to 0.67 (Balsa to Red Oak)
Paper - 0.80
HDPE - 0.95
ABS - 1.06
PVC - 1.35
Fibre - 1.94
Steel - 7.80
Aluminum - 2.71

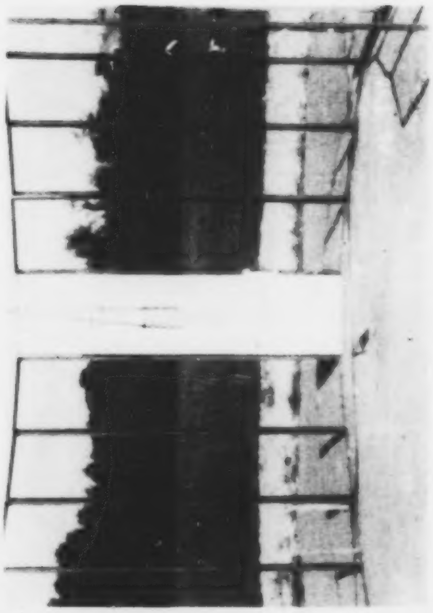

Figure 1 - Typical set-up

Figure 2 - 155 mm mortar driven 30 cm into the ground

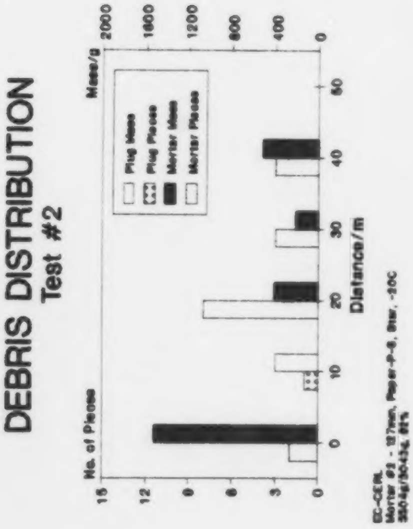

Figure 3 - Typical fragment distribution graph

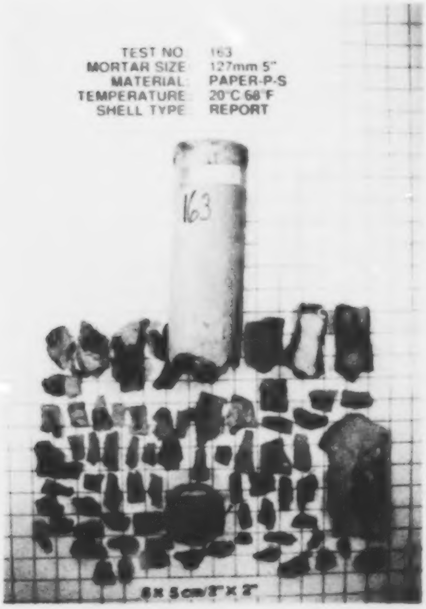
TEST NO 163
MORTAR SIZE 127mm 5"
MATERIAL PAPER-P-S
TEMPERATURE 20°C 68°F
SHELL TYPE REPORT
163
5 X 5 cm/2" X 2"

Figure 4 - Many fragments due to paper layers separating

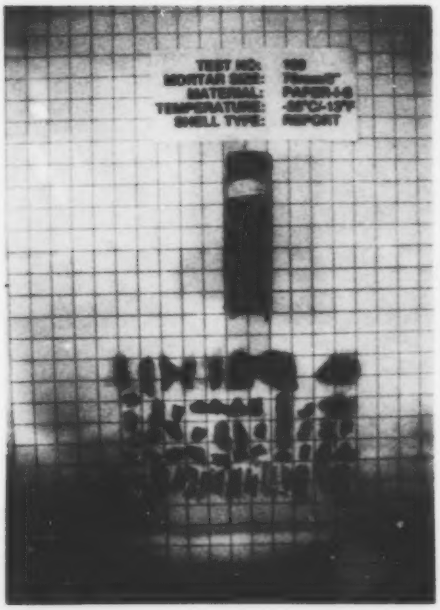
TEST NO:
MORTAR SIZE:
MATERIAL:
TEMPERATURE:
SHELL TYPE:
REPORT

Figure 5 - Less layer separation
with impregnated paper

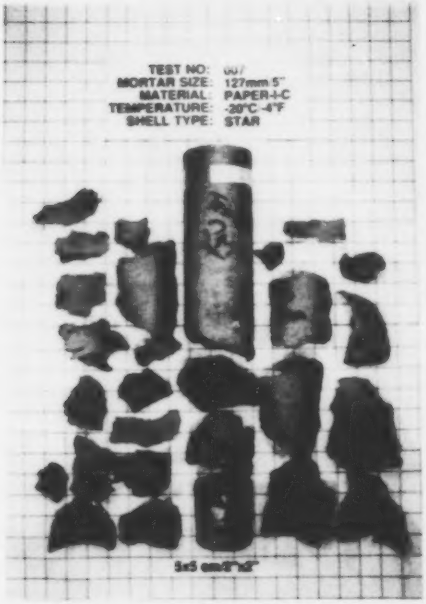
TEST NO:
MORTAR SIZE: 127mm 5"
MATERIAL: PAPER-I-C
TEMPERATURE: -20°C -4°F
SHELL TYPE: STAR
5x5 cm/2"x2"

Figure 6 - Clear separation of paper layers

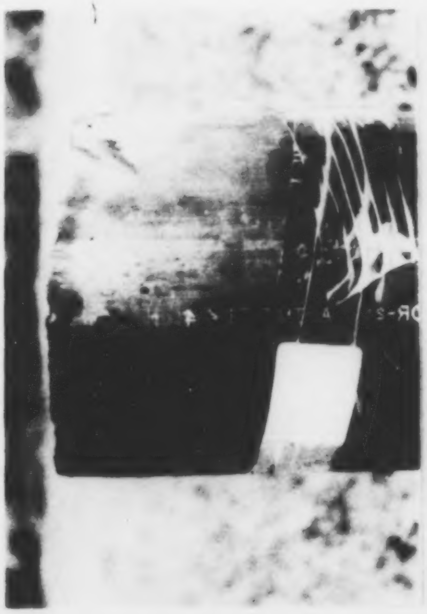

Figure 7 - Poorly cut HDPE mortar

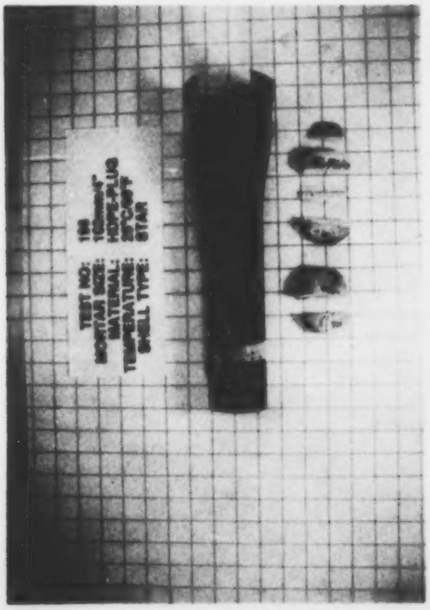
TEST NO:
MORTAR SIZE:
MATERIAL: HDPE-PLUG
TEMPERATURE:
SHELL TYPE: STAR

Figure 8 - Splitting of HDPE mortar
due to a star shell

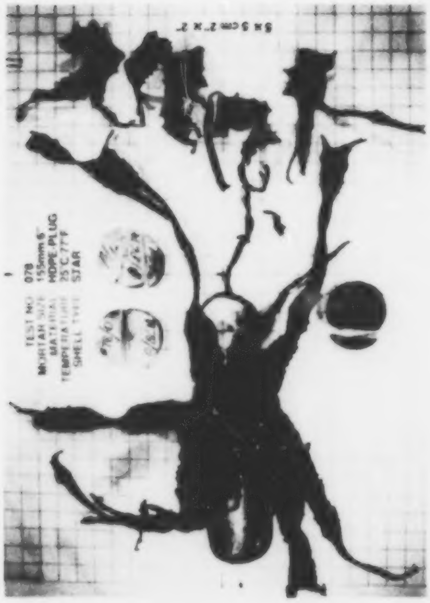
5 x 5 cm 2" x 2"
TEST NO: 078
MORTAR SIZE: 155mm 6"
MATERIAL: HDPE-PLUG
TEMPERATURE: 25°C 77°F
SHELL TYPE: STAR

Figure 9 - Severe mangling of HDPE r
due to a star shell

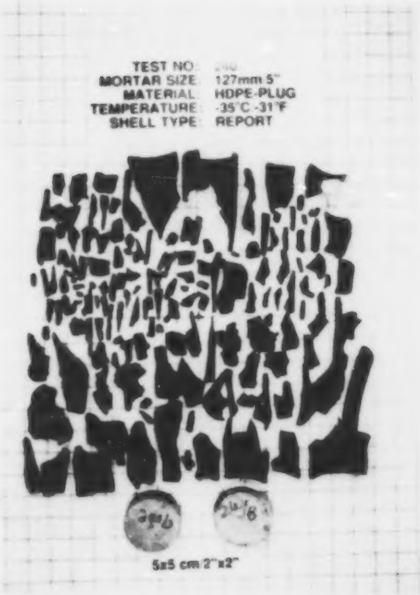
TEST NO:
MORTAR SIZE: 127mm 5"
MATERIAL: HDPE-PLUG
TEMPERATURE: -35°C -31°F
SHELL TYPE: REPORT
5x5 cm 2"x2"

Figure 10 - Brittle fracture of a HDPE mortar
due to a report shell

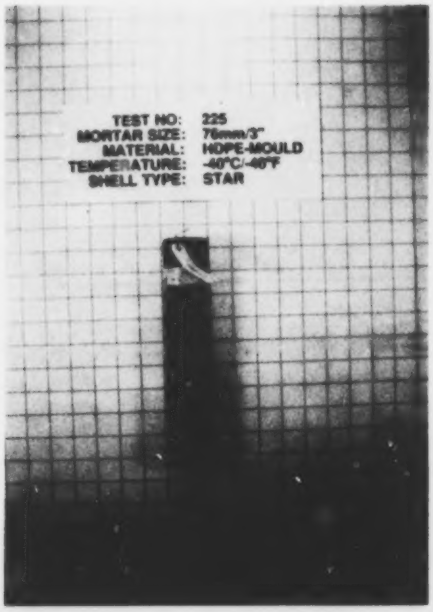
TEST NO: 225
MORTAR SIZE: 76mm/3"
MATERIAL: HDPE-MOULD
TEMPERATURE: -40°C/-40°F
SHELL TYPE: STAR

Figure 11 - A blow moulded HDPE mor

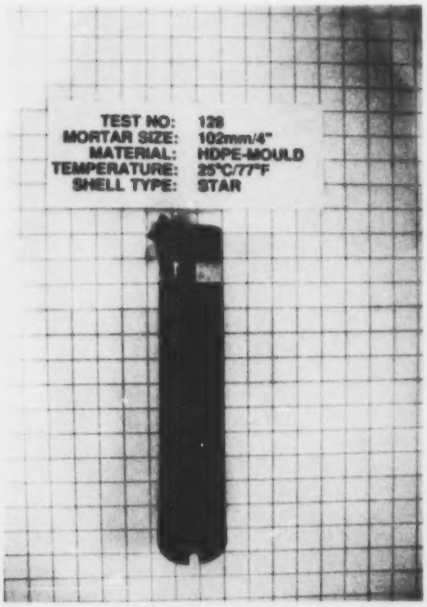
TEST NO: 128
MORTAR SIZE: 102mm/4"
MATERIAL: HDPE-MOULD
TEMPERATURE: 25°C/77°F
SHELL TYPE: STAR

Figure 12 - Star shells simply split
the moulded HDPE mortar

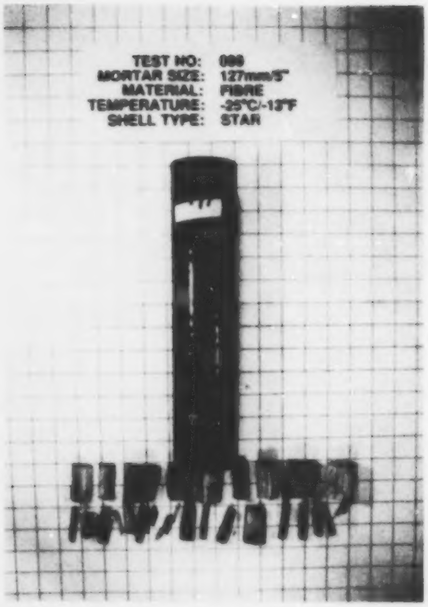
TEST NO: 086
MORTAR SIZE: 127mm/5"
MATERIAL: FIBRE
TEMPERATURE: -25°C/-13°F
SHELL TYPE: STAR

Figure 13 - Star shells did not cause any damage to the fibre reinforced tube

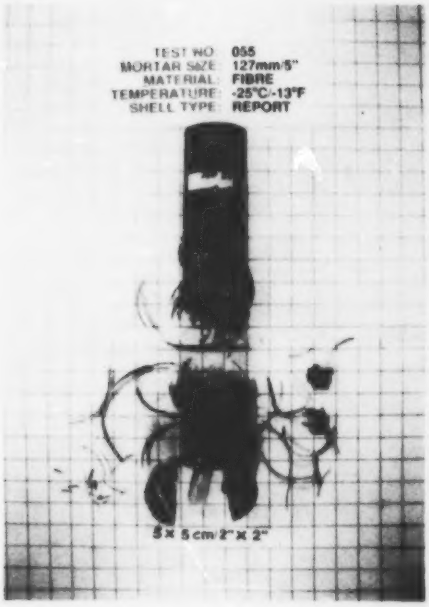
TEST NO: 055
MORTAR SIZE: 127mm/5"
MATERIAL: FIBRE
TEMPERATURE: -25°C/-13°F
SHELL TYPE: REPORT
5 x 5 cm/2" x 2"

Figure 14 - Fibre reinforced mortar damaged by a report shell

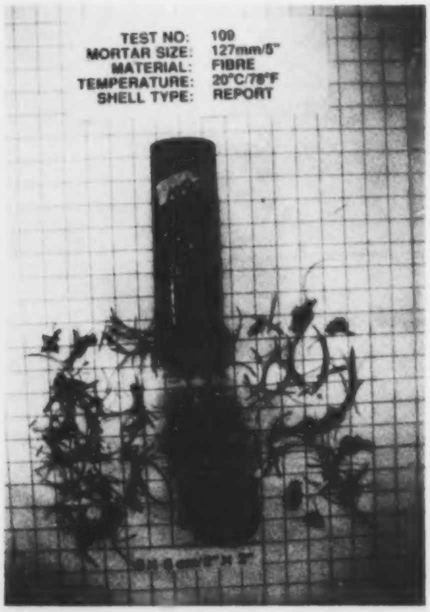
TEST NO: 109
MORTAR SIZE: 127mm/5"
MATERIAL: FIBRE
TEMPERATURE: 20°C/78°F
SHELL TYPE: REPORT

Figure 15 - Fibre reinforced mortar damaged by a report shell

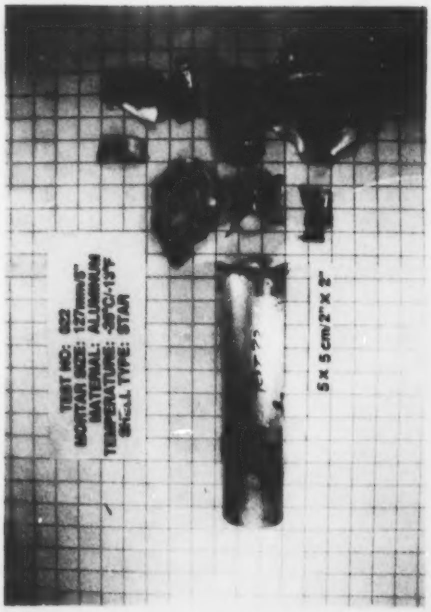
TEST NO: 022
MORTAR SIZE: 127mm/5"
MATERIAL: ALUMINUM
TEMPERATURE: -25°C/-13°F
SHELL TYPE: STAR
5 x 5 cm/2" x 2"

Figure 16 - Damage to an aluminum mortar by a star shell

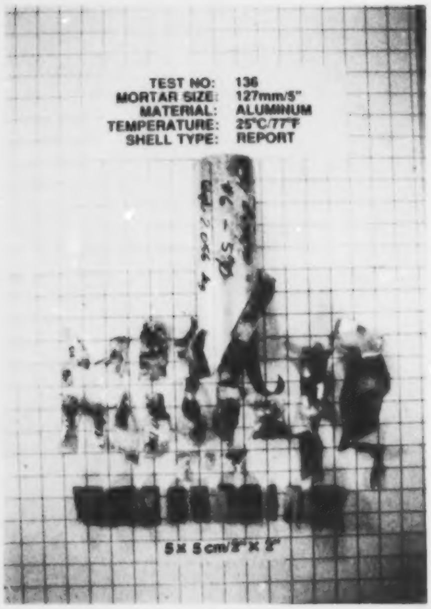
TEST NO: 136
MORTAR SIZE: 127mm/5"
MATERIAL: ALUMINUM
TEMPERATURE: 25°C/77°F
SHELL TYPE: REPORT
5 X 5 cm/2" X 2"

Figure 17 - Damage to an aluminum mortar by a report shell

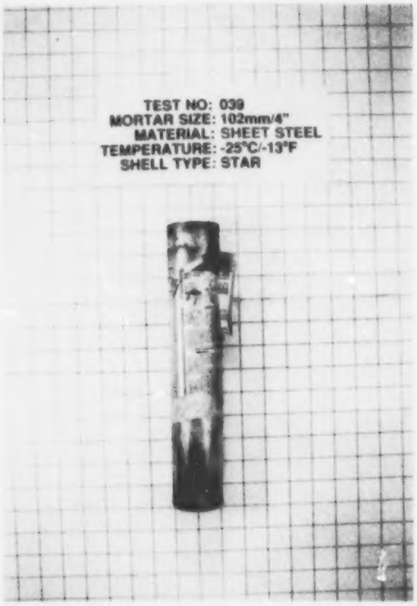
TEST NO: 039
MORTAR SIZE: 102mm/4"
MATERIAL: SHEET STEEL
TEMPERATURE: -25°C/-13°F
SHELL TYPE: STAR

Figure 18 - Sheet metal mortar tested with 102 mm star shell

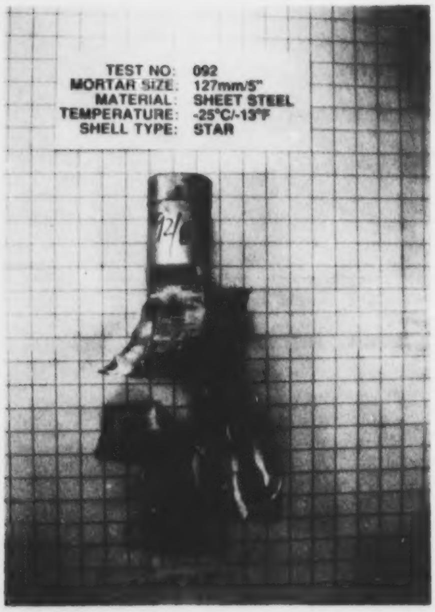
TEST NO: 092
MORTAR SIZE: 127mm/5"
MATERIAL: SHEET STEEL
TEMPERATURE: -25°C/-13°F
SHELL TYPE: STAR

Figure 19 - Sheet metal mortar tested with 127 mm star shell

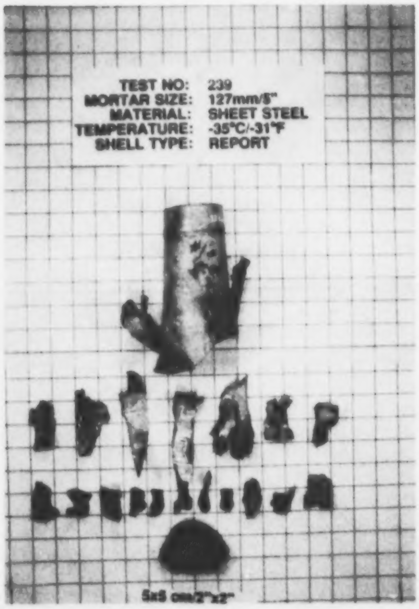
TEST NO: 239
MORTAR SIZE: 127mm/5"
MATERIAL: SHEET STEEL
TEMPERATURE: -35°C/-31°F
SHELL TYPE: REPORT
5x5 cm/2"x2"

Figure 20 - Damage to a sheet steel mortar due to a report shell

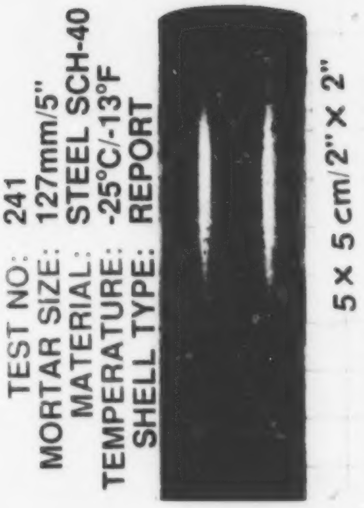
TEST NO: 241
MORTAR SIZE: 127mm/5"
MATERIAL: STEEL SCH-40
TEMPERATURE: -25°C/-13°F
SHELL TYPE: REPORT
5 x 5 cm/2" x 2"

Figure 21 - Crack in steel mortar due to a report shell

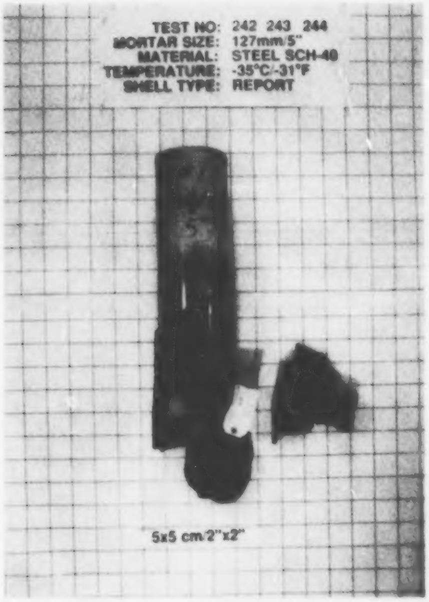
TEST NO: 242 243 244
MORTAR SIZE: 127mm/5"
MATERIAL: STEEL SCH-40
TEMPERATURE: -35°C/-31°F
SHELL TYPE: REPORT
5x5 cm/2"x2"

Figure 22 - Burst steel mortar after repeated tests with report shells

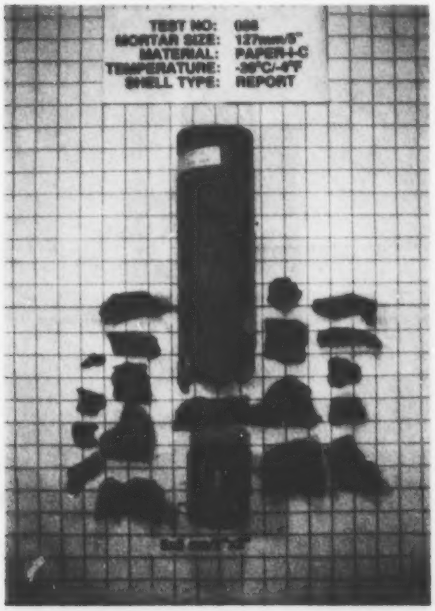
TEST NO:
MORTAR SIZE: 127mm/5"
MATERIAL: PAPER-I-C
TEMPERATURE: -20°C/-4°F
SHELL TYPE: REPORT

Figure 23 - Damage to paper mortar due to a report shell

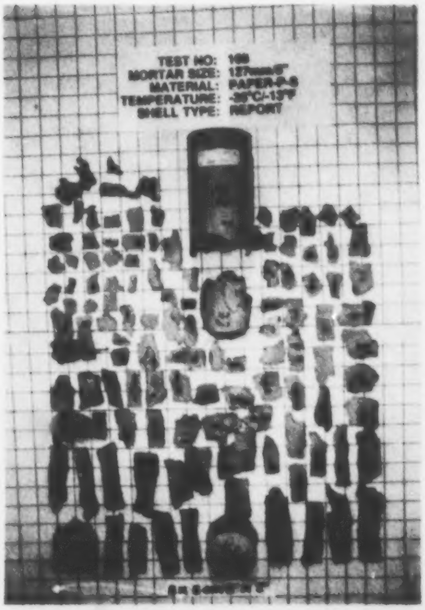
TEST NO:
MORTAR SIZE: 127mm/5"
MATERIAL: PAPER-P-S
TEMPERATURE: -25°C/-13°F
SHELL TYPE: REPORT

Figure 24 - Damage to paper mortar by a report shell

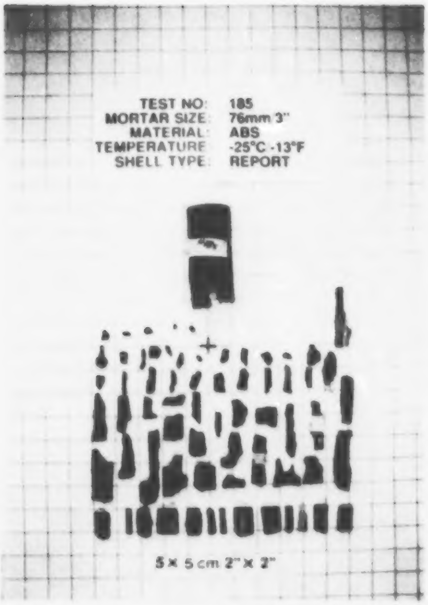
TEST NO: 185
MORTAR SIZE: 76mm 3"
MATERIAL: ABS
TEMPERATURE: -25°C -13°F
SHELL TYPE: REPORT
5 × 5 cm 2" × 2"

Figure 25 - Damage to ABS1 mortar by a report shell

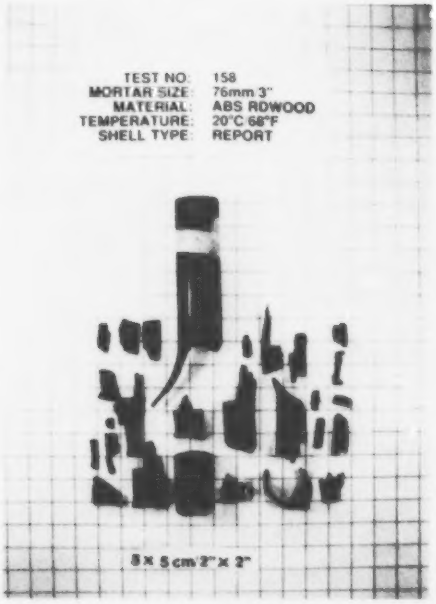
TEST NO: 158
MORTAR SIZE: 76mm 3"
MATERIAL: ABS RDWOOD
TEMPERATURE: 20°C 68°F
SHELL TYPE: REPORT
5 × 5 cm 2" × 2"

Figure 26 - Damage to ABS2 mortar by a report shell

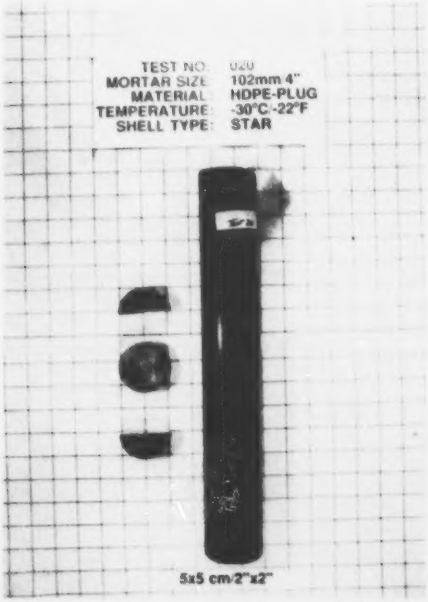
TEST NO: 020
MORTAR SIZE: 102mm 4"
MATERIAL: HDPE-PLUG
TEMPERATURE: -30°C -22°F
SHELL TYPE: STAR
5x5 cm/2"x2"

Figure 27 - Star shells tended to blow plug out of HDPE mortar

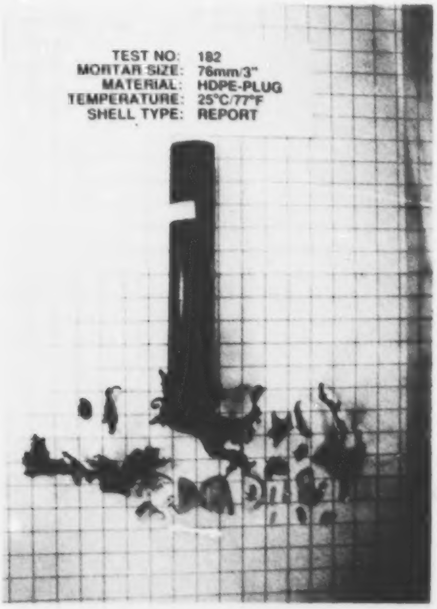
TEST NO: 182
MORTAR SIZE: 76mm/3"
MATERIAL: HDPE-PLUG
TEMPERATURE: 25°C/77°F
SHELL TYPE: REPORT

Figure 28 - Typical damage to plugged HDPE mortar by a report shell

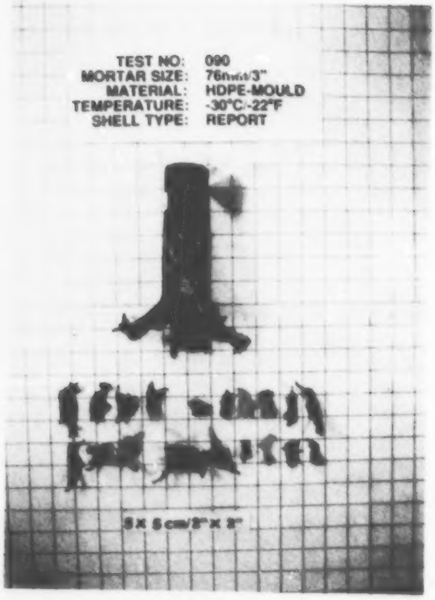
TEST NO: 090
MORTAR SIZE: 76mm/3"
MATERIAL: HDPE-MOULD
TEMPERATURE: -30°C/-22°F
SHELL TYPE: REPORT
5 X 5 cm/2" X 2"

Figure 29 - Typical damage to moulded HDPE mortar by a report shell

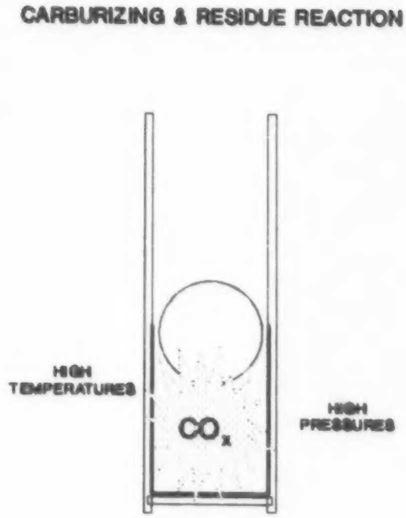
CARBURIZING & RESIDUE REACTION
HIGH TEMPERATURES
HIGH PRESSURES
CO$_x$

Figure 30 - Carburizing process in a steel mortar

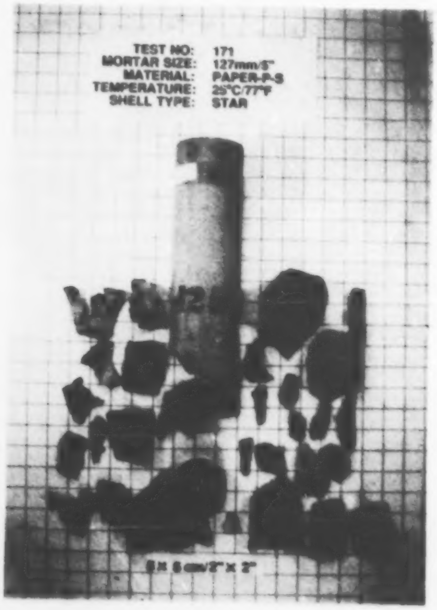
TEST NO: 171
MORTAR SIZE: 127mm/5"
MATERIAL: PAPER-P-S
TEMPERATURE: 25°C/77°F
SHELL TYPE: STAR
5 X 5 cm/2" X 2"

Figure 31 - Damage to paper mortar by a star shell

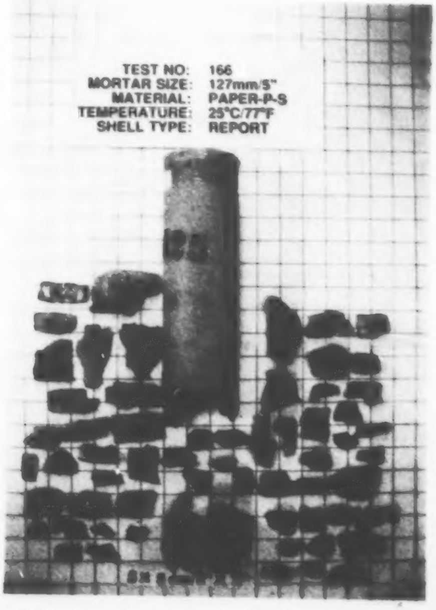
TEST NO: 166
MORTAR SIZE: 127mm/5"
MATERIAL: PAPER-P-S
TEMPERATURE: 25°C/77°F
SHELL TYPE: REPORT

Figure 32 - Damage to paper mortar by a report shell

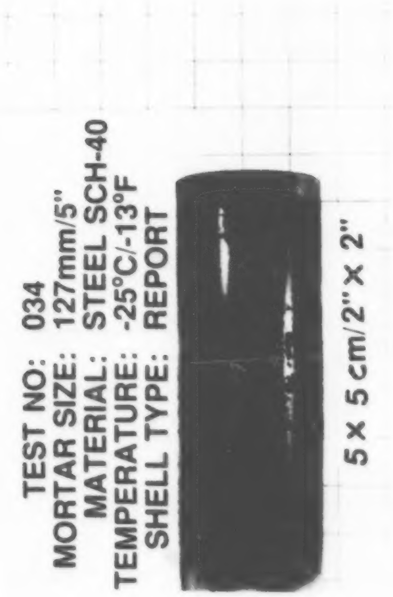
TEST NO: 034
MORTAR SIZE: 127mm/5"
MATERIAL: STEEL SCH-40
TEMPERATURE: -25°C/-13°F
SHELL TYPE: REPORT
5 × 5 cm/2" × 2"

Figure 33 - Damage to a steel mortar by a report shell

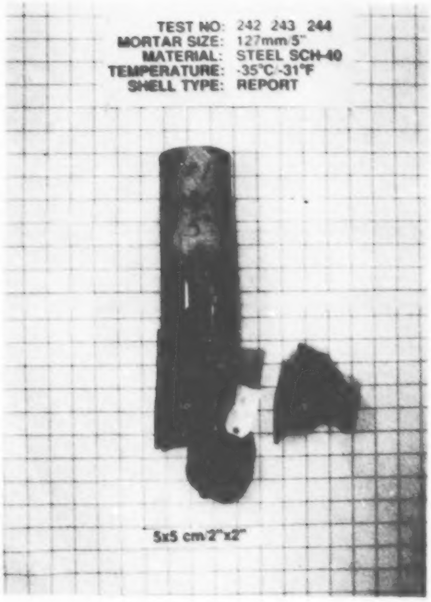
TEST NO: 242 243 244
MORTAR SIZE: 127mm/5"
MATERIAL: STEEL SCH-40
TEMPERATURE: -35°C/-31°F
SHELL TYPE: REPORT
5x5 cm/2"x2"

Figure 34 - Damage to a steel mortar by a report shell

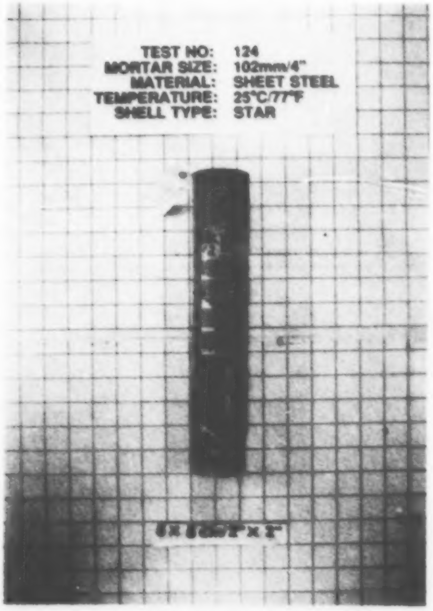
TEST NO: 124
MORTAR SIZE: 102mm/4"
MATERIAL: SHEET STEEL
TEMPERATURE: 25°C/77°F
SHELL TYPE: STAR
5 x 5 cm/2" x 2"

Figure 35 - Damage caused by a 102 mm star shell to a sheet steel mortar

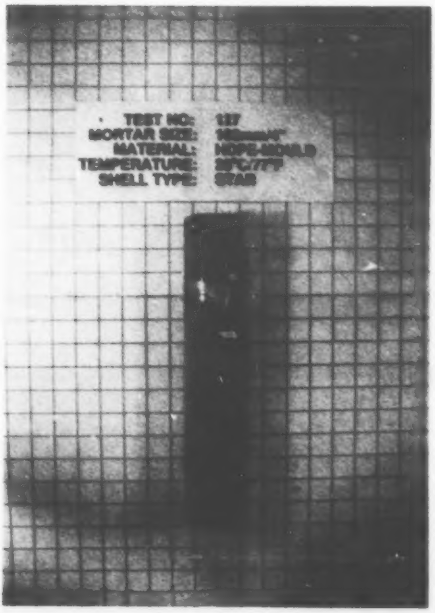
TEST NO: 127
MORTAR SIZE: 102mm/4"
MATERIAL: HDPE-MOULD
TEMPERATURE: 25°C/77°F
SHELL TYPE: STAR

Figure 36 - Damage caused by a 102 mm star star shell to a moulded HDPE mortar

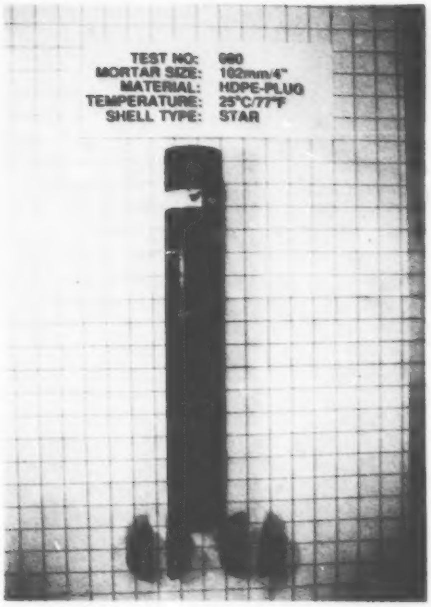
TEST NO: 080
MORTAR SIZE: 102mm/4"
MATERIAL: HDPE-PLUG
TEMPERATURE: 25°C/77°F
SHELL TYPE: STAR

Figure 37 - Damage caused by a 102 mm star shell to a plugged HDPE mortar

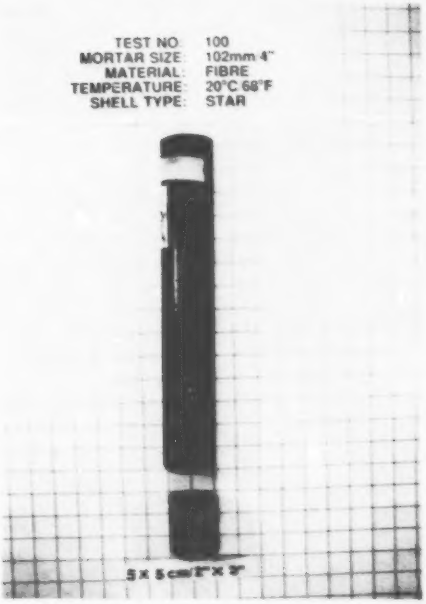
TEST NO 100
MORTAR SIZE 102mm 4"
MATERIAL FIBRE
TEMPERATURE 20°C 68°F
SHELL TYPE STAR
5 X 5 cm/2" X 2"

Figure 38 - Damage caused by a 102 mm star shell to a fibre reinforced mortar

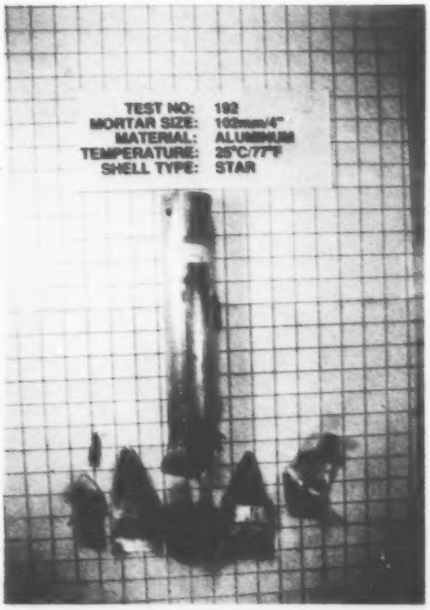
TEST NO: 192
MORTAR SIZE: 102mm/4"
MATERIAL: ALUMINUM
TEMPERATURE: 25°C/77°F
SHELL TYPE: STAR

Figure 39 - Damage caused by a 102 mm star shell to an aluminum mortar

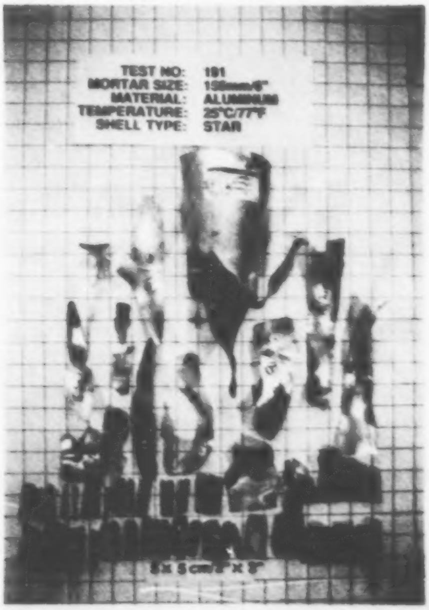
TEST NO: 191
MORTAR SIZE: 155mm/6"
MATERIAL: ALUMINUM
TEMPERATURE: 25°C/77°F
SHELL TYPE: STAR
5 X 5 cm/2" X 2"

Figure 40 - Damage caused by a 155 mm star shell to an aluminum mortar

THE RELATIVE EFFECTIVENESS OF FIREWORK SHELLS AS ENERGETIC MATERIALS

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ABSTRACT

As part of an investigation on the effect of fireworks shells exploding in mortars, the Canadian Explosives Research Laboratory (CERL) undertook a project to determine the TNT equivalent of report shells. This paper presents some of the initial work and the results of tests designed to demonstrate the relative effectiveness of firework shells to various other energetic materials when fired in steel pipes.

The results indicate that the TNT equivalent of report shells is dependent on the scaled distance. The tests performed with the energetic materials in steel pipes give a graphical representation of their relative strength. Using the number of fragments produced as the indicator for relative effectiveness, the rating is as follows: star shell, black powder, report shell, TNT, and dynamite.

RÉSUMÉ

Dans le cadre d'une étude des effets de l'explosion d'obus pyrotechniques dans des mortiers, le Laboratoire canadien de recherche sur les explosifs (LCRE) a entamé un projet en vue de déterminer l'équivalent TNT des obus sonores. Le rapport décrit certains des premiers travaux et les résultats d'essais visant à montrer l'efficacité relative, par rapport à d'autres formes de matériel énergétique, d'obus pyrotechniques mis à feu dans des tuyaux d'acier.

Les résultats indiquent que l'équivalent TNT des obus sonores est fonction de la distance étalonnée. Les essais entrepris sur le matériel énergétique dans des tuyaux d'acier fournissent une représentation graphique de la puissance relative. En utilisant le nombre de fragments produits pour indiquer l'efficacité relative, le matériel est coté comme suit: obus à étoile, poudre noire, obus sonore, TNT et dynamite.

INTRODUCTION

The Canadian Explosives Research Laboratory (CERL) has the mandate to test fireworks for the Chief Inspector of Explosives for the purpose of having such items authorized in Canada. In support of this effort it was decided to determine the TNT equivalent of firework report shells (1) so as to obtain a better appreciation for the hazards associated with shells accidentally functioning in a mortar. The TNT equivalent is also useful for determining the hazards associated with other activities such as storage, transport and use, and should be considered when establishing safety distances.

Presented in graphical form with pressure as a function of scaled distance, the data can then be used to estimate the overpressure for various distances from the source and for shells containing various masses of pyrotechnic composition. One must, however, be aware of the procedure used to generate TNT equivalency data. Most explosives normally have an energy output for a given initiator that has some dependency on confinement. The underlying assumption with some studies is that, unconfined or not, the explosive is detonating at or close to its ideal value. This may not be the case with pyrotechnic compositions such as those found in fireworks.

As point sources, chemical explosives and to a lesser extent, pyrotechnics, are not comparable to nuclear explosives. That is, their energy is released over a finite volume and often, especially if not properly initiated, the source could behave as many point sources in motion. This behaviour gives rise to errors in both the mass of and the distance from the charge which are two parameters used to determine the TNT equivalent. As an example, a plastic bag containing 200 g of powdered TNT can be initiated with a high strength electric detonator and on detonation the blast pressure monitored. The measured pressures and impulses will not compare favourably with those normally quoted in the literature. They will be lower. A careful search of the area after the blast will reveal unreacted explosive. Thus, an uncertainty will exist in the mass of the reacted explosive and because of the dispersive action of the blast, in the distance. Similarly, the broad spectrum of pyrotechnics will give TNT equivalents that may not only be highly dependent on confinement, sample configuration, and mass but also on the distance from the charge.

The work presented in this report was performed from the practical consideration of functioning single or multiple report shells and it must be emphasized that the TNT equivalent is valid solely for such situations.

To compliment the TNT equivalency data and give a feel for their hazard potential, various amounts of several energetic materials were functioned in steel pipes. The resulting fragmentation was used to rate the materials on a relative effectiveness scale. However, no attempt was made to use a scale factor to compensate for the amount of material used as was done with the TNT equivalency data.

EXPERIMENTAL SET-UP

Report shells from two manufacturers were tested. Both 50 mm shells contained the same amount of composition, whereas the 76 mm shells from manufacturer [B] contained approximately three times as much composition as those from manufacturer [A].

Blast pressures were measured at various distances for single and multiple 50, 76, 102, and 127 mm diameter report shells and for full cases of shells functioning 'en masse'. The overpressure was then plotted as a function of Z, the scaled distance, where Z is determined by dividing the distance measured from the centre of the charge (report shells) to the blast gauge, by the cube root of the mass of the charge (pyrotechnic composition).

The shells had their outside wrap, fuse and lift charge removed. Then an electric match was taped to the delay composition so that the shell could be functioned remotely. String was used to suspend the shell one meter above the ground from a wire stretched taut between two steel support bars. When more than one shell was used, they were taped together side-by-side and hung in the same manner as a single shell. In the tests with the case loads of report shells, the case was set on styrofoam supports so that its centre was 1 m above the ground.

Four, lollipop-style, blast gauges (2), rigidly clamped 1 m above the ground to steel posts and located at 0.5 m intervals from the shells were used to detect the overpressures. The TNT equivalent was then determined from the pressures as the ratio of the mass of TNT to that of the pyrotechnic composition that will produce the same peak overpressure at a specified distance.

To determine the relative effectiveness of the various energetic materials, steel pipe nipples were loaded as indicated in Fig. 1. The samples were tested by hanging and firing them in an explosion tank as indicated in Fig. 2.

The black powder charges and firework shells were ignited with an electric match while the dynamite and TNT were initiated with a commercial, high strength (HS), electric detonator (0.8 g of PETN base charge). The explosive samples were first loaded in small plastic bags. Then the detonator was placed in the sample and the bag was bound and inserted in the pipe. The firework shells were not altered. The complete shell was loaded into the pipe assembly with the electric match connected to the instantaneous fuse. A 5 mm diameter hole drilled on the side of the pipe was used for passing the initiator wires which were then connected to a firing line.

After each test, the pipe fragments, if any, were collected, weighed and compared to its initial mass. The mass of the pipe and two caps assembly varied from 1.09 kg to 1.14 kg. The fragments were then counted and photographed.

DISCUSSION RESULTS

The fitted data for the single and multiple shells, including the full case tests have been plotted as a function of distance so that one may readily appreciate the attenuative effect that distance has on the peak pressure. Details are reported in reference (1). In general, as expected, (See Fig. 3) the pressure increases as the size of the shell (and the mass of the composition) increases. Within each shell size the same effect is noticed in Fig. 4, with increasing number of shells. Also, as expected and indicated in Fig. 5, the pressures for shells from manufacturer B, which contained more composition, are greater than those from manufacturer A. From these graphs it is obvious that the simplest protection against blast overpressures is distance.

Finally, Fig. 6 shows the average experimental data values and the corresponding fitted pressure data plotted as a function of scaled distance. Also plotted is the overpressure pressure for TNT charges derived from the equation given in reference (4).

Entering Fig. 6 with a pressure of 237 kPa (the highest available value from the fitted line), the corresponding scaled distances for the report shells and TNT are 1.08 m/kg$^{1/3}$ and 1.87 m/kg$^{1/3}$, respectively. Then, at the same distance, the TNT equivalent is determined to be 0.19 for the above range of scaled distances. Entering with pressures of 100 kPa and 30 kPa results in TNT equivalents of 0.32 and 0.54 respectively. At lower pressures, the TNT equivalent value becomes constant at 0.59. Thus the TNT equivalent is lower at the higher pressures. That is, as one nears the charge or increases the charge mass (small Z values), the reaction behaviour of TNT and the report shells must be very different.

Although an almost constant TNT equivalent would be expected from most high explosives, this is not the case with the report shells. Using the same method as above, the third curve in Fig 6 was generated to indicate the trend of the TNT equivalent as a function of the scaled distance.

Figure 6 can be entered with one or any two of the variables (mass, distance or pressure). Knowing the mass of the charge (composition), one can determine the resulting blast pressure at a particular distance. Another example would be a situation where one knows the maximum tolerable overpressures at a given distance from a process (or storage area) and wishes to determine the maximum amount of process material.

The results from the steel pipe tests are listed in Table 1. All the pipe assemblies sustained damage except for the one tested with the high strength electric detonator and those loaded with 28 and 35 g of 2FA black powder. In these tests, the reaction gases simply vented through the 5 mm detonator wire hole on the side of the pipe.

All the firework shells functioned instantaneously even though they were ignited through the fuse. The star shells (gross mass - 100 g) produced from 4 to 9 fragments (Fig. 7), approximately the same number as that produced by 200 g of black powder (Fig. 8). On average, the report shell caused twice the damage as star shells with the number of fragments (Fig. 9) ranging from 9 to 19. The report shells contained 35 g of composition and 15 g of lift charge.

A 28 g charge of TNT (-100 mesh) burst the pipe into 37 pieces (Fig. 10) whereas, the same amount of dynamite (gelatin 75%) produced 66 fragments (Fig. 11). The same tests were repeated with 35 g of the above explosives. The TNT and dynamite produced 81 and 116 fragments, respectively, as indicated in Figures 12 and 13.

When the pipe was completely filled with 117 g of TNT (Density - 0.6 g/cc), it burst into more than 1000 pieces. The results can be seen in Fig. 14. Ninety seven percent of the initial mass of the pipe assembly was recovered. On sieving, 567 fragments (1.02 kg - 93% of recovered mass) were left on the #6 sieve, 342 fragments (0.03 kg - 3% of recovered mass) were left on the #8 sieve, and the remaining 4% (0.04 kg) went through the #8 sieve.

A similar test was performed by filling the pipe with 235 g of dynamite (Density - 1.3 g/cc). The results are shown in Fig. 15. Again, in excess of 1000 fragments were produced. Seventy nine percent of the initial mass of the pipe was recovered, indicating that a substantial amount of the pipe was pulverized. Much of this would have been imbedded on the walls of the blast tank. On sieving, 910 fragments (0.84 kg - 94% of recovered mass) were left on the #6 sieve, 490 fragments (0.04 kg - 5% of recovered mass) were left on the #8 sieve, and the remaining 1% (0.01 kg) went through the #8 sieve.

The results of the pipe burst tests have been listed in Table 1 in order of increasing number of fragments. The third column of the table has been labelled the Relative Effectiveness Factor where the number of fragments produced by the 35 g of TNT was used as the reference. As with the TNT equivalent results, the data are only applicable for the stated criteria; in this case, the number of fragments produced. It is obvious that the results not only reflect such parameters as the properties and amount of energetic material but also confinement and test conditions. Some of this data have been plotted in Fig. 16.

CONCLUSIONS

Blast overpressures were measured for report shells of various sizes and arrangements. Over the scaled distance range of 1 $m/kg^{1/3}$ to 7.5 $m/kg^{1/3}$, the report shells are less energetic than TNT. Their TNT equivalent is not constant but is dependent on the scaled distance and varies from 0.2 to 0.6.

As already mentioned, the TNT equivalent of a particular material must be quantified within the context by which it was determined. Only within such constraints can such data be used to determine hazards that may be associated with the particular material or article.

With the number of fragments used as the criterion to determine the effectiveness factor, relative to 35 g of TNT, the report shells have a value of 0.23. This value falls in the lower range (0.2 to 0.6) as determined from blast pressure measurements. It can be argued that this could have been expected since the lower TNT equivalents occur in the low Z value range (Refer to Fig. 6) and the location of the witness to damage, the pipe wall, is definitely in this region. That is, the pipe wall is very close to the explosive material.

As expected, the degree of damage as indicated by the number of fragments, is not only proportional to the amount of test material but also on its energy and configuration which include such factors as density and confinement. The results obtained from the tests performed with the energetic materials in steel pipes give an indication of their relative strength. Using the number of fragments produced as the indicator for relative effectiveness, the rating is as follows: star shell, black powder, report shell, TNT, and dynamite.

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3. E. Contestabile, et al., Evaluation of fireworks mortars, Canadian Explosives Research Laboratory, Mining Research Laboratories, CANMET, Energy, Mines and Resources, Canada, MRL 91-051(TR), 1991.

4. Kinney, G.F., Explosive shocks in air, Springer-Verlag, New York, USA, 1985.

5. Explosives and Demolitions, Department of the Army Field Manual, FM 5-25, Headquarters Department of the Army, Washington, D.C., USA.

Table 1 - Relative effectiveness of fireworks shells to energetic materials (Criterion - Number of fragments)

Material	Amount /g	Number of Fragments	Relative Effectiveness Factor
HS Detonator (PETN)	0.8	0	----
Black Powder (2FA)	28	0	----
Black Powder (2FA)	35	0	----
Star Shell (50mm)	(100 gross)	4-9	0.11
Black Powder (2FA)	200	9	0.11
Report Shell (50mm)	(35+15)	9-19	0.23
TNT (-100 mesh)	28	37	0.46
Dynamite (Gelatin 75%)	28	66	0.81
TNT (-100 mesh)	35	81	1.00
Dynamite (Gelatine 75%)	35	116	1.43
TNT (-100 mesh)	117	567*	----
Dynamite (Gelatin 75%)	235	910*	----

*Fragments on #6 sieve

Table 2 - Relative effectiveness of various explosives (5)

Explosive	Relative Effectiveness Factor	Velocity of Detonation m/s
TNT	1.00	6900
PETN	1.66	7300
RDX	1.50	8300
C-4	1.34	8000
Tetryl	1.25	7100
Straight Dynamite 40%	0.65	4600
(Commercial) 50%	0.79	5500
60%	0.83	5800
Ammonia Dynamite 40%	0.41	2700
(Commercial) 50%	0.46	3400
60%	0.53	3700
Gelatin Dynamite 40%	0.42	2400
(Commercial) 50%	0.47	2700
60%	0.76	4900
75%	1.00+	6300
AN	0.42	3400
Black Powder	0.55	400

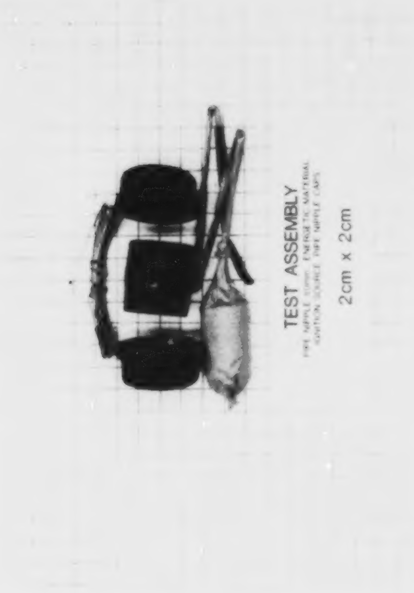

Figure 1 - Steel pipe, caps and test material

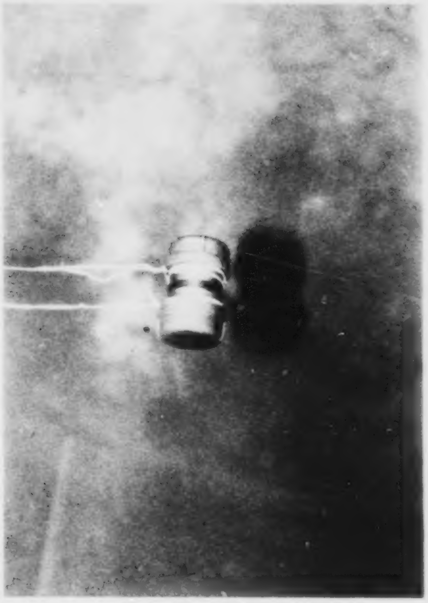

Figure 2 - Test pipe hanging in explosion tank

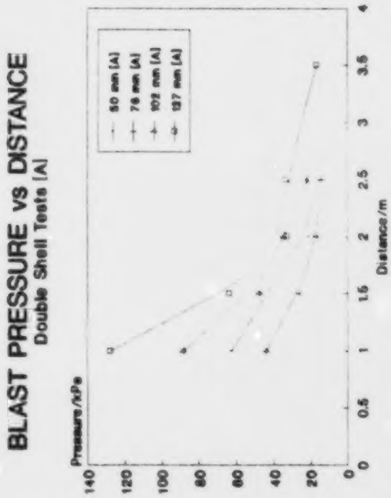

Figure 3 - Peak pressure versus distance for various shells

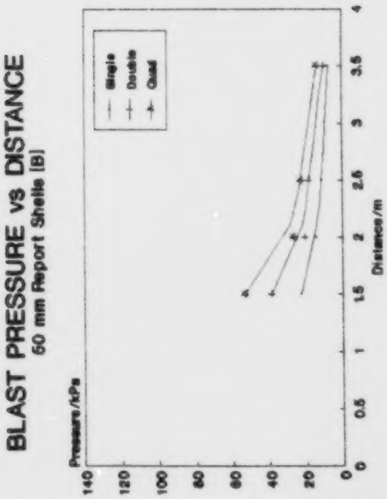

Figure 4 - Peak pressure versus distance with increasing number of shells

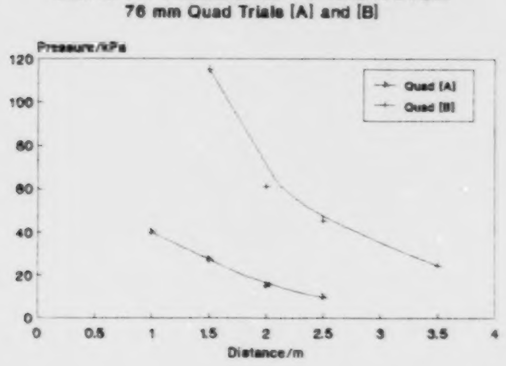

Figure 5 - Peak pressure versus distance for two shell types

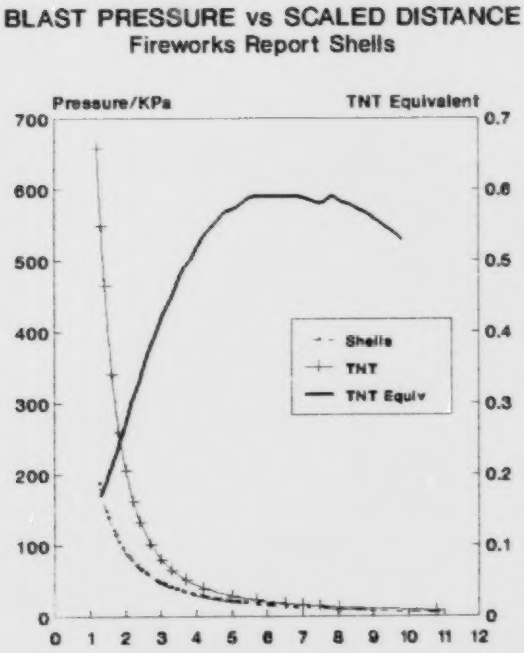

Figure 6 - Peak pressure and TNT equivalent versus scaled distance

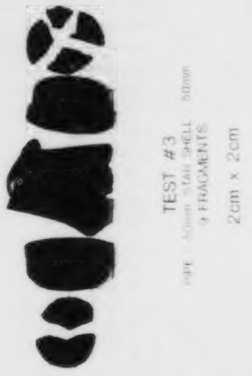
TEST #3
PIPE 50mm STAR SHELL 50mm
9 FRAGMENTS
2cm x 2cm

Figure 7 - Typical damage caused by a 50 mm star shell to pipe and caps

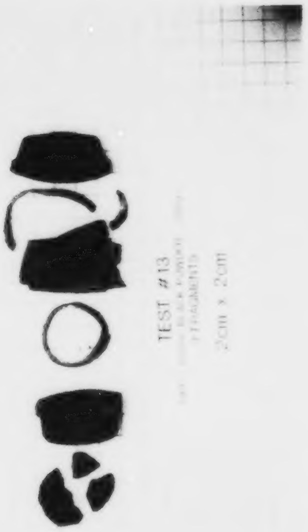
TEST #13
2cm x 2cm

Figure 8 - Damage caused by 200 g of 2FA black powder

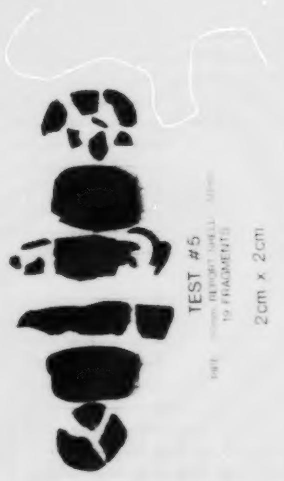
TEST #5
REPORT SHELL
19 FRAGMENTS
2cm x 2cm

Figure 9 - Typical damage caused by a 50 mm report shell to pipe and caps

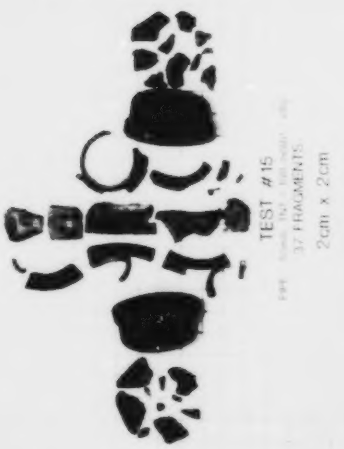
TEST #15
37 FRAGMENTS
2cm x 2cm

Figure 10 - Damage caused by 28 g of TNT

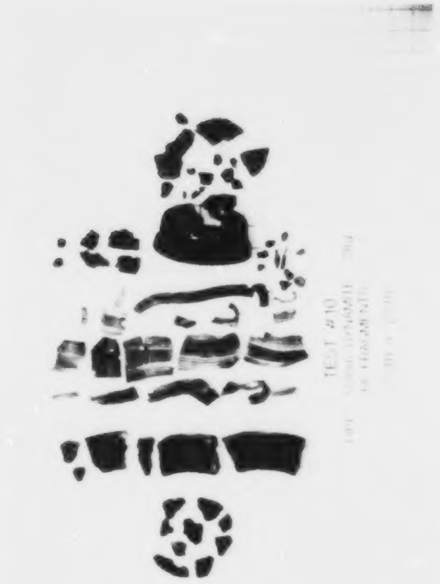

Figure 11 - Damage caused by 28 g of Dynamite

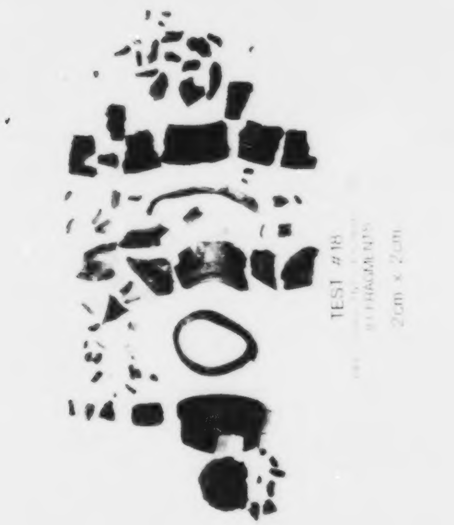
TEST #18
2cm x 2cm

Figure 12 - Damage caused by 35 g of TNT

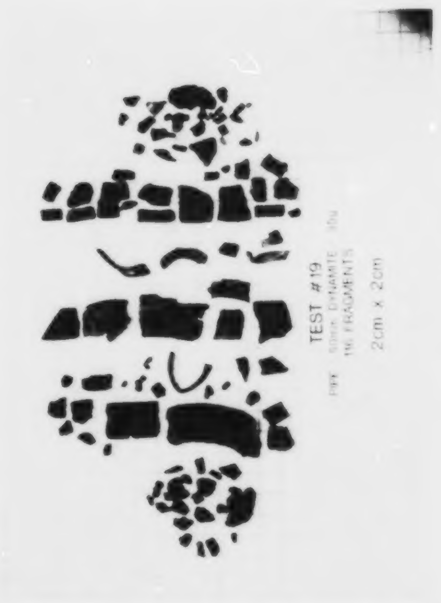
TEST #19
16 FRAGMENTS
2cm x 2cm

Figure 13 - Damage caused by 35 g of Dynamite

TEST #16
2cm x 2cm

Figure 14 - Damage caused by 117 g of TNT

TEST #11
DYNAMITE

Figure 15 - Damage caused by 235 g of Dynamite

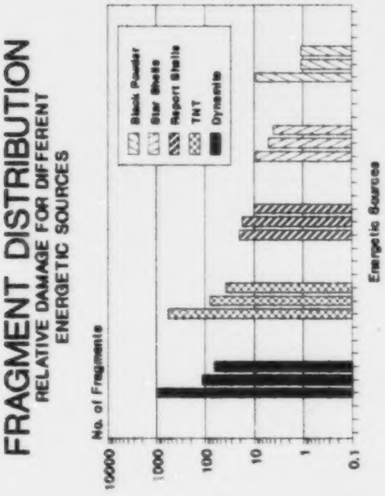

Figure 16 - Fragment distribution as a function of energetic sources

ENVIRONMENTAL EFFECTS OF FIREWORKS ON BODIES OF WATER

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ABSTRACT

The effects of fireworks decomposition products (FWDP) on the environment are unknown. The infrequence of fireworks displays at most locations, coupled with the wide dispersion of constituents, make detection of FWDP difficult. The present study was conducted to evaluate the impact of repeated fireworks displays (2,000 shows over a decade) on a small lake (WSL) located at EPCOT Center in Lake Buena Vista, Florida. Water chemistry data for WSL were collected from 1982 until the present, and sediments were characterized early in 1992. Heavy fireworks loading has not caused eutrophication or otherwise affected aesthetic characteristics of WSL, but it has added detectable amounts of barium, strontium and antimony to the water and sediments. The mass of antimony and barium in the surface sediments of WSL was found to be approximately 100X greater than that in the water column, demonstrating that these elements accumulate principally as insoluble compounds. Gradual increases in water column concentrations of antimony and barium over the past decade have paralleled the cumulative number of fireworks displays at the site. While current water column concentrations of these metals in WSL are higher than those of nearby lakes, these levels are not thought to be harmful to aquatic biota. Site-specific characteristics that will influence impacts of FW-borne constituents include size of the water body, hydraulic residence time, water and sediment physico-chemical characteristics, and cumulative fireworks loading over time. Data from this study suggest that environmental impacts from FWDP typically will be negligible in locations that conduct fireworks displays infrequently. Antimony may prove to be a good chemical "marker" for detecting fireworks activity at infrequently loaded sites, since for WSL, a close balance was found between the amount of antimony loaded from fireworks and the mass residing in the sediment and water column.

INTRODUCTION

Fireworks (FW) displays impose a variety of stresses upon local environments. These are manifested as the noise, explosive fiery, smoke and fallout debris that occur over communities during holidays and other festive occasions. Most of these effects are predictable, expected and short-lived.

The acute and chronic environmental impacts resulting from fireworks decomposition products (FWDP), however, are unknown. FWDP include a wide range of inorganic metals and organic polymer residues. The starting pyrotechnic composition consisting of oxidizers, fuels and binders, once reacted, produce a variety of metal oxides and particulate organics that fall to earth. Many of these metals (e.g., sodium, potassium, barium, strontium, magnesium and aluminum) comprise the cation in the various oxidizing agents, which typically are provided as nitrate and/or chlorate salts (1). Additionally, some metals (e.g., barium and strontium) are incorporated in FW to produce color effects. In most locations, the infrequence of FW displays and the wide spatial dispersion of constituents make it difficult to detect FWDP, or to evaluate their environmental impacts.

A small lake in central Florida has been the site of almost 2,000 fireworks displays in the past decade. This lake provides an ideal site for quantifying the long term accumulation of FWDPs, and of evaluating their environmental impacts. In the present study, we present findings on the accumulation of selected FWDP in the sediment and water column of this lotic system.

METHODS

Site Description

The study site is World Showcase Lagoon (WSL), a man-made lake located in EPCOT Center, Lake Buena Vista, FL, USA. The WSL is approximately 17.5 hectares in area, with an average depth of 3.5m. The lake volume is approximately 612,500 m^3. The hydraulic residence time for WSL is long: the only water inputs to this system are from rainfall and a small groundwater pump located at a nearby attraction. WSL receives no direct stormwater inputs, but considerable boat traffic and nearby maintenance activities (e.g., painting) may contribute contaminants to the system. Fireworks are thought to be a prominent contributor of particulate constituents to WSL. During FW displays, pyrotechnic devices are launched above WSL from the shoreline, as well as from barges anchored in the center of the lake. WSL is not utilized for recreation (no direct human contact occurs), nor is the lake used as a source of drinking water.

Field and Laboratory Techniques

Since 1982, quarterly water column measurements at two sites in WSL have been conducted for nutrients, metals and other general limnological parameters (e.g., alkalinity, conductivity, total organic carbon [TOC], pH and chloride). In January 1992, mid-depth water samples were collected from six sites in WSL. These samples were analyzed by ion chromatography for fluoride, chloride, nitrate, sulfate, alkalinity, sodium, potassium, magnesium and calcium.

Sediment samples also were collected from six sites in WSL during January 1992. These sediment cores (collected to a 20 cm depth) were partitioned into 4 depth increments: 0-2 cm; 2-5 cm; 5-10 cm; and 10-20 cm. Aliquots from each sediment layer were subjected to microwave digestion with acid, and the digestates were analyzed by ICP/MS (Inductively Coupled Plasma Mass Spectrometry). This instrument provided quantitative information for several metals, including chromium, manganese, iron, nickel, copper, zinc, antimony, barium and strontium.

The mass per unit area (in the top 20 cm of sediment) for selected metals in WSL was calculated as the product of sediment concentration and bulk density (dry mass per volume). This average value was then multiplied by the bottom area of the lake to provide an estimate of total mass of a particular metal in the WSL sediments.

An estimate of FWDP loading to WSL was calculated as follows. The mass (gross weight) of pyrotechnic devices exploded over WSL since 1982 was provided by entertainment personnel at EPCOT Center. A rough estimate of the composition of these FW was obtained from the pyrotechnic literature. Total mass loading to WSL by a particular constituent was estimated as the product of total FW mass and the average FW constituent concentration.

RESULTS AND DISCUSSION

Water Column and Sediment Characteristics

Water quality characteristics of WSL were summarized for three periods: during 1982 and 1983, prior to the extensive use of fireworks at the site; during 1987 and 1988, after the display of approximately 1,000 fireworks shows; and, January 1992, after display of nearly 2,000 shows (Tables 1 & 2). It should be noted that in 1989, WSL was connected to another lake system via a narrow canal. Hence, subsequent changes in water quality may have been due to mixing or dilution, rather than to activities occurring within or around the lake.

Of the non-metal constituents, total kjeldahl nitrogen (ammonium + organic forms) and alkalinity were the only water column parameters that changed substantially during the first five year period (Table 1). Alkalinity continued to increase during the subsequent five years, and slight increases in nitrate-N and chloride were also observed during this period. The major anion and cation analytes measured in 1992 in WSL all occur at concentrations typical of freshwater systems (Table 2). The nitrogen, phosphorus and total organic carbon concentrations show that WSL can be classified as an oligo-mesotrophic lake (2). The trophic status of WSL did not change during the 10 year study, and no marked changes in biota (aquatic macrophytes, fish or phytoplankton populations) were observed.

While most chemical and biological characteristics in WSL showed little temporal variation (Table 1), water column antimony (Sb) and barium (Ba) concentrations in WSL increased linearly from 1982 until 1989 (Fig. 1). The increase in concentrations of these elements in the water column undoubtedly was due to FW activity, since both of these elements are common constituents in pyrotechnic devices. Concentrations of other metals (copper, zinc, cadmium, manganese and selenium) remained unchanged in WSL during the study. The decline in water column concentrations of Ba and Sb in 1989 (Fig. 1) probably was due to the dilution of WSL waters with that of the adjacent lake.

Metals concentrations in WSL sediments were highest in the top sediment layer (0-2 cm), and declined with depth (Fig. 2). For most metals, WSL surface sediment concentrations (Table 3) were typical of natural or "non-impacted" sediments (3). However, an unusual feature of WSL sediments is that Sb, Ba and strontium (Sr) were found in moderate to high concentrations. Little information on "typical" sediment concentrations for these metals could be found, but it is known that they usually occur at concentrations much lower than those of zinc, manganese and lead. Strontium, like Ba and Sb, is a common firework constituent (1) with few other commercial uses. Aluminum and magnesium also are used in pyrotechnic devices, but these were not analyzed for in the present study due to their high native concentrations in Florida soils and sediments.

While surface sediments displayed highest metals concentrations (e.g., Fig. 2), this sediment layer also was the least consolidated, with the lowest amount of dry mass per unit volume. The bulk density of 0-2 cm, 2-5 cm, 5-10 cm, and 10-20 cm sediment layers averaged 0.15, 0.68, 1.21, and 1.71 g/cm^3, respectively. Consequently, differences in total mass of metals among the sediment depth layers was not as pronounced as would be suggested by concentration differences. For example, the mean mass of Sb per unit area at 0-2 cm, 2-5 cm, 5-10 cm, and 10-20 cm sediment depths in WSL was 8.3, 13.0, 27.6, and 4.9 g/m^2, respectively.

The total mass of Sb, Ba and Sr in the WSL sediments (top 20 cm) was estimated to be 9,400, 84,000 and 18,500 kg, respectively. The spatial variability in concentrations of these metals in WSL sediments was high (due either to uneven depostion or to variations in native metals concentrations), so the above mass values should be considered rough approximations. Additionally, we have not yet quantified "natural" levels of these elements in nearby soils and lake sediments, so the percentage of these metals in WSL contributed by FW is unknown.

Antimony was selected for a mass balance calculation because it has a very low crustal abundance of 0.2 mg/kg (4). For purposes of this comparison, we therefore have assumed that all Sb in WSL was derived from fireworks. The total mass of Sb dissolved in the water column was estimated (using 1988 "maximum" concentration values) to be 200 kg. WSL therefore contains 9,600kg Sb, only 2.1% of which is in a dissolved form. The total mass loading of Sb to the WSL from pyrotechnic devices was estimated to be 11,800 kg, a value in fairly close agreement to the calculated mass of Sb in the water column and sediments. That most of the Sb is detectable in WSL is not surprising, since this element is not used as a nutrient by either plants or animals, and is not likely to be transported from the system.

A similar mass balance conducted for Ba was less precise: 84,500 kg of Ba was found in the WSL system (0.6% of which is in the water column), but only 19,000 kg of Ba was calculated to have been loaded from FW displays. The poor agreement between the calculated mass of Ba loaded from FW and the mass observed in WSL is likely due to an underestimate in the amount of Ba utilized in the pyrotechnic devices, or to high native Ba levels in the WSL sediments.

Environmental Impacts of Fireworks Decomposition Products

Fireworks activity does not appear to contribute substantially to the eutrophication of water bodies. FW contain almost no phosphorus (1), which frequently is the "growth-limiting" nutrient for aquatic plants. FW do contribute nitrogen, an element that can stimulate unwanted plant (micro- or macroscopic) growth. However, the biochemical N cycle in aquatic systems is dynamic, and there are several pathways through which N is lost to the atmosphere in gaseous forms (5). In WSL, a small lake with very heavy fireworks loading, no visible decline in the aesthetic quality (e.g., appearance of nuisance algae) of the system has occurred.

This study demonstrates that a principal environmental impact of FW activity is the deposition of selected metals. In WSL, a site that has received heavy FW loading for a decade, the FW-derived metals Ba, Sr and Sb were found both in the water column and sediments. These metals are deposited in largely insoluble forms, since in WSL, 97.9% of the Sb and 99.4% of the Ba occur in the sediments. Fireworks contain other metals (e.g., aluminum, magnesium and copper) that also are deposited in dryfall, but high "background" or native concentrations of these elements may render the small mass of metals contributed by FW difficult to detect. Antimony may prove to be a good chemical "marker" for detecting fireworks activity at infrequently loaded sites, since for WSL, a close balance was found between the amount of antimony loaded from fireworks and the mass residing in the sediment and water column.

The environmental consequences of FW metal deposition are difficult to discern. For any aquatic system over which FW are displayed, environmental impacts of FWDP will depend on the area and depth of the water body, hydraulic residence time, water and sediment physico-chemical characteristics, and total fireworks loading. For most sites that conduct FW displays infrequently, environmental impacts of FWDP probably are negligible. In contrast, a "worst-case" scenario would be where heavy, routine fireworks loading is conducted over a small, relatively stagnant body of water that is utilized as a drinking water source. It would be prudent to conduct periodic monitoring for metals at such locations, because both Sb and Ba at low levels are under consideration for various surface water and drinking water priority lists (6).

Data on FWDP presented herein suggest a number of topics that merit further study. These include: evaluating factors that influence speciation and mobility of fireworks metals in aquatic systems; evaluating techniques for reducing concentrations of selected analytes within FW shells; and, investigating the efficacy of binding FW-borne metals in lake sediments by chemical immobilization. In order to ensure that environmental impacts are understood and minimized, more detailed studies on the chemistry of FW-borne metals likely will be conducted in WSL during the coming decade.

ACKNOWLEDGEMENTS

Field and analytical assistance from the Reedy Creek Improvement District Environmental Laboratory is gratefully acknowledged. Preston Merrick and Eddie Snell provided the authors with historical water quality data for WSL. Sediment coring in WSL was conducted by Karen and Jim Peterson. Chris Coston performed ion chromatograph analyses on WSL water samples collected in 1992.

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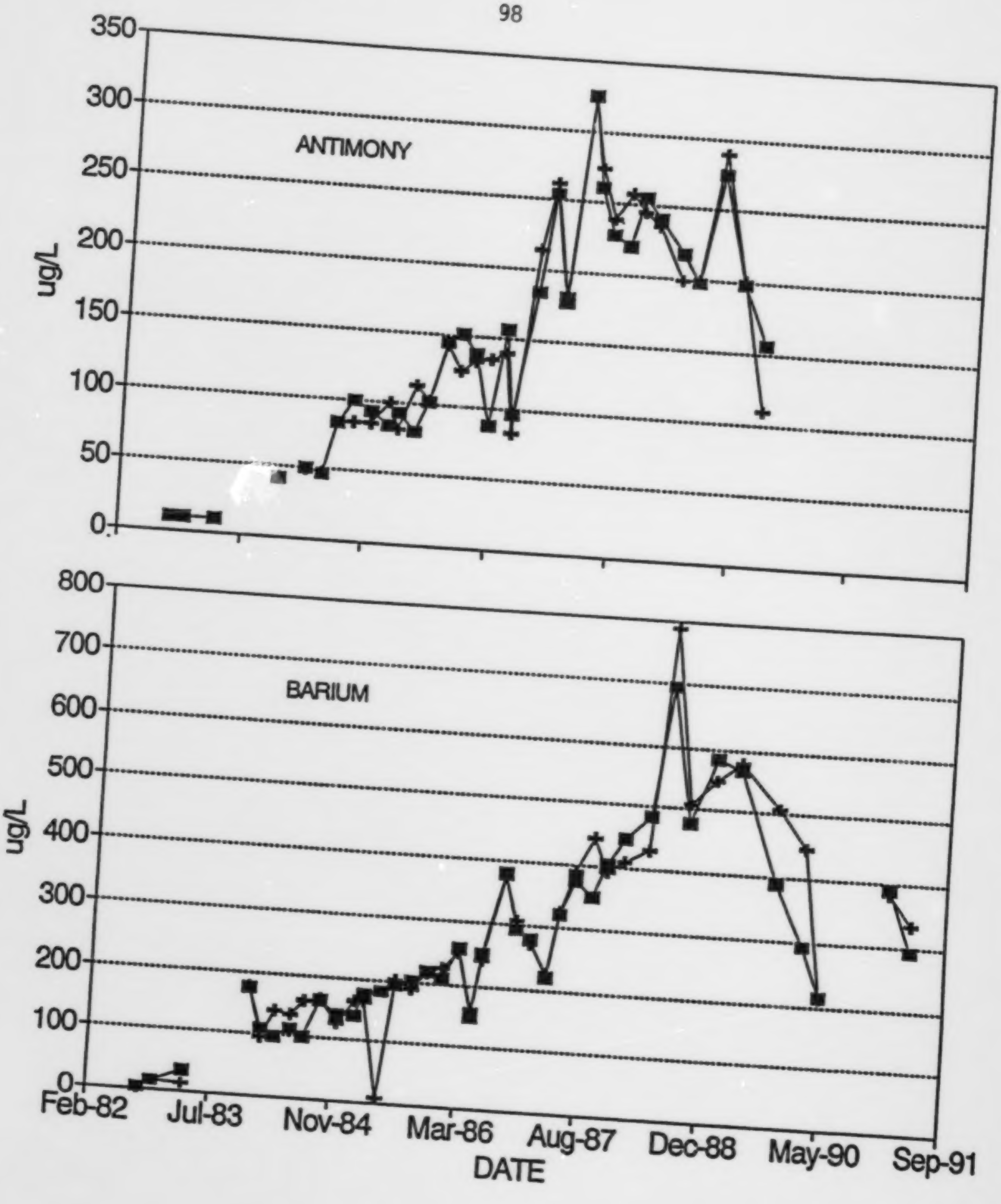

Figure 1. World Showcase Lagoon (WSL) water column antimony and barium concentrations from 1982 through 1991. The two symbols on each graph depict values from separate surface water sampling stations.

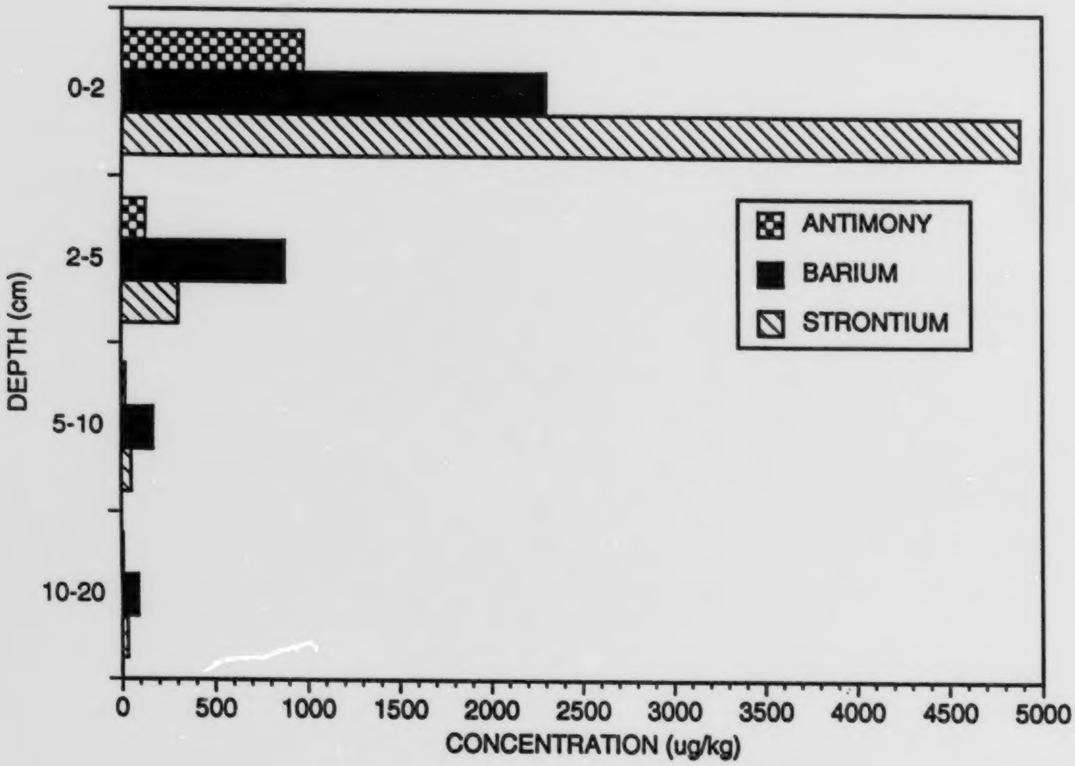

Figure 2. Concentrations of strontium, barium and antimony with sediment depth in WSL. These values are from one core sample collected on the east side of WSL.

Table 1. Mean water quality characteristics for WSL at a mid-lake sampling station before (1982-1983) and after (1987-1988) five years of heavy fireworks loading.

analyte	1982-1983	1987-1988
Total Kjeldahl N (mg/L)	0.22	0.40
Ammonium-N (mg/L)	0.05	0.04
Nitrate-N (mg/L)	0.06	0.05
Total phosphorus (mg/L)	0.03	0.02
Total organic C (mg/L)	3.3	3.8
Chloride (mg/L)	6.0	6.2
Conductivity (umhos/cm)	174	162
Alkalinity (mg/L)	29.4	57.0

Table 2. Mean anion and cation concentrations (mg/L) for WSL at mid-lake sampling stations in January 1992. Median reference values (with ranges) are from a study of 165 Florida lakes (7). Other data references are cited below.

analyte	WSL	Reference Values
Fluoride	0.14	0.26[1]
Chloride	8.7	14 (2 - 2300)
Ammonium-N	0.02	NA
Nitrate-N	0.10	NA
Sulfate-S	11.1	11 (3.4 - 186)
Alkalinity	72.0	10 (0 - 204)
Sodium	4.2	7.6 (1 - 1200)
Potassium	2.6	1.3 (0 - 51)
Magnesium	5.0	4.1[2]
Calcium	24.4	1.5[2]

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1 Reference #2
2 Reference #4

NA - not available

Table 3. Mean metal concentrations for surface (0-2 cm) sediments from WSL, January 1992. Values reflect the mean of six sampling sites.

Metal	WSL Sediment (mg/kg)	Natural or Non-Impacted Sediments[1] (mg/kg)
Iron	189	< 17,000
Barium	23.2	NA
Copper	8.9	< 25
Antimony	7.6	NA
Strontium	4.8	NA
Zinc	1.97	< 90
Manganese	0.77	< 300
Lead	0.70	< 90
Chromium	1.47	< 25
Nickel	0.67	< 20

1 Reference #3

NA - not available

FIREWORKS MANUFACTURING AND SAFETY VIDEO

by

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ABSTRACT

The objectives of this video are to describe the manufacturing process of fireworks, identify the Federal regulations pertaining to fireworks manufacturers, and identify safety equipment and procedures an ATF employee must utilize when inspecting fireworks manufacturing facilities.

INTRODUCTION

Fireworks are an important part of many celebrations primarily around the Fourth of July but increasingly used throughout the year. What steps are involved in making these spectacular effects? How are chemicals, cardboard, and glue combined to produce these patterns and colors high in the sky? What precautions are necessary to produce these devices safely? Explosive mixtures are used to make fireworks. ATF's regulations address the manufacturing of all fireworks as well as the importation, storage and distribution of special fireworks, the larger types used in public displays. The importation, distribution, and storage of common fireworks, the type intended for consumer use, are not regulated by ATF. The purpose of this video is to familiarize you with the procedures associated with the manufacturing of special fireworks and to cover regulations and safety factors related to performing inspections at fireworks manufacturing facilities.

COMPONENTS OF FIREWORKS

Fireworks contain various chemical mixtures consisting of oxidizers, fuels, binders, special effects or color producing agents, and propellants.

OXIDIZERS

Oxidizers are one of the necessary components used to manufacture explosives. They provide the oxygen necessary to support the combustion of the fuel in the fireworks composition by releasing oxygen when heat is applied. Common examples of oxidizers are perchlorates and nitrates.

FUELS

Fuels are the second element of an explosive mixture and serve to produce heat when oxidized. Mixed with an oxidizer, they form a compound which when ignited produces a rapid decomposition, or an explosion. Fuels are always stored separately from oxidizers. Commonly used fuels are aluminum, magnesium and red gum.

BINDERS

Binders help keep the explosive mixture together during manufacture and storage. Common binders are starch and dextrine.

COLOR PRODUCING AGENTS AND SPECIAL EFFECTS

These chemicals are added to create colored flame in the burning mixture. Some examples of color producing agents are strontium nitrate or strontium carbonate for a red flame, barium nitrate or barium chlorate for a green flame, and aluminum for white flame.

Other chemicals may be added to create special effects such as smoke or a loud noise called a "report." Potassium nitrate and sulfur mixtures are often used to make smoke while flash powder, a mixture usually containing potassium perchlorate and aluminum, creates reports and flashes of light.

PROPELLANTS

Black powder is used as the propellant lift charge and as the break or bursting charge in aerial fireworks. It is also mixed with the color producing materials to assist igniting them. Black powder is composed of potassium nitrate, charcoal and sulfur and several grades of fineness are used in the manufacture of fireworks.

CONTAINERS

The remaining components used in manufacturing fireworks are items such as cardboard tubes, craft paper, string, glue, paste and fusing.

MANUFACTURING PROCESS

The manufacturing of fireworks involves the mixing or blending of chemicals into an explosive mixture. This mixing is followed by the assembly process in which blended explosive materials are put into containers and fused.

MIXING

The first process involved in the manufacturing of fireworks is the mixing of various raw materials such as fuels, oxidizers, binders, and color or other special effect producing agents according to a specific formula. This mixing is done by hand through a screen as seen here or by machines similar to portable cement mixers. The raw materials may be ground at the fireworks manufacturing plant or purchased in a usable form and stored separately until needed. As many as 6 to 7 chemicals may be used, depending on the effect to be created. The individual chemicals are weighed out in the proper ratio and worked through a screen creating the fireworks mixture.

This mixture, now an explosive, is sifted through screens of varying sizes to produce a well blended powder. These powders are stored in fiber drums or boxes and placed in appropriate magazines until they are ready to be used. Flash powder, used to make salutes, is a particularly dangerous explosive and regulations limit the quantity that can be prepared at any one time to 10(lbs). Extreme care is required for all operations involving flash powder to protect against flame and sparks.

The mixing, whether by hand or machine, is done in a processing building. Processing buildings, if heated, should use only steam, hot water, or other non-flame or non spark producing heating methods. Electrical wiring must be in non-sparking conduits, and dust tight covers should be present over all electric lights. Mixing and other processing buildings must meet the table of distance requirements for the amount of explosives contained in them, which may never exceed 500 lbs of pyrotechnic materials or 10 lbs of flash powder. Because the mixing process may produce a great deal of dust, mixing is often done outdoors where there is better ventilation. Because of the dusty conditions and potential explosion hazard, mixing operations are usually performed by only one operator. Also, due to the high degree of hazard associated with mixing operations, inspectors should not bepresent in buildings while mixing is taking place. Mixing personnel should wear cotton clothing to minimize static charge generation. They should also wear dust masks or respirators to prevent the powdery mixtures from being inhaled and should wear aprons or coveralls to prevent powder from adhering to their clothing. The mixing area is thoroughly cleaned out after a particular formula has been prepared. This will prevent potentially dangerous chemicals from accidentally coming into contact with each other as well as ensuring that unwanted materials do not enter the mix.

STAR MANUFACTURING.

The dry mixtures prepared at the mixing building are then taken to another process building where they may be pressed in cylindrical tubes to produce fountain or water fall type effects. Other powders are formed into "stars", the color producing pyrotechnic effects used in aerial shells and roman candles. To make stars, the powdered explosive is moistened with water or a water-alcohol blend.

As seen here, it is often done outdoors in stainless steel basins. The mixture is kneaded to the consistency of bread dough or putty. A commonly used technique for making stars is to put the damp composition into a wooden form and pack it with a wooden mallet into a cake or loaf shape. The loaf is brought to a cutting table which is covered with a fine grade of black powder. The black powder acts like flour in baking; it prevents the star mixture from sticking to the table top or cutting instruments, which are made from a non-sparking material.

The loaf is cut into slices of varying widths depending on the size of the star to be made, usually 1/4" - 3/4". The slices are cut again, usually the same width as the first cut, resulting in cubes. These cubes are rolled in black powder, which serves to act as a primer for igniting the stars when the shell bursts. They are then put into trays to dry, which takes between 4 and 24 hours and can be done inside or outdoors.

The star making process can also be done by machine. The dry powders are moistened in a mixer and fed into a press which forms the stars, which are then set out to dry.

The building where stars are made is considered a process building and should have all the safety features mentioned earlier as well as meet all the requirements, including separation distances, imposed by Federal regulations. As mentioned previously, the workers should again wear cotton clothing, and an apron to prevent the mixtures from getting on their clothes and to cover sparking materials such as belt buckles and zippers. As with the mixing building, this room and all the tools are thoroughly cleaned after each type of star is processed. This is done for safety reasons and for product integrity. Star compositions when wet, are considered to be in-process and are considered to be explosives once they have dried.

LOADING.

Loading or filling begins the assembly of the aerial display shell, the most commonly used type of special fireworks. In this type of process building operations such as loading, priming, or wrapping may occur.

The filling process will depend on the type of shell to be made. The general process involves hand or machine loading pyrotechnic materials into a cardboard tube of the appropriate size. Flash powder is used for salutes, stars for color effect shells and both for a multi-effect display. The filling demonstrated here shows a typical color and report shell. A measured amount of flash powder is hand loaded into a cardboard tube of the appropriate size, wrapped, and fused. This is now a salute and must be stored as a high explosive when packaged in bulk quantities. This will form the report or flash and sound effect of the shell. For a color effect heavy craft paper is wrapped around the top of the shell to create a pocket to hold the stars and break charge of black powder. The stars may be sorted through a screen to ensure that only ones of a certain size are put into some specialty displays.

A tube shaped metal form is placed in the center of the shell. This will create a space for the bursting charge. The stars are then hand packed into the shell around the tube as tightly as possible to obtain a better break, as the black powder break charge reacts to the force acting against it.

After packing in the stars, a measured amount of black powder is poured into the metal tube in the center of shell. The excess black powder spills over the top of the stars, which serves to act as an igniting charge, and the metal tube is removed. A cardboard disk with the time fuse is then inserted on the top of the shell. The time fuse determines when the display explodes. The top of the paper is folded down around the shell, closing it up. Another cardboard disk may be placed over the time fuse, creating the top of the shell and holding the time fuse in place. Each special fireworks manufacturer has their own, often unique, procedure for finishing aerial shells so operations observed during an inspection may differ somewhat from those shown in this video.

SPIKING

The next step used by many manufacturers in the assembly of aerial shells is spiking. String soaked in wheat paste, which helps to tighten it around the display, is wrapped around the shell. This helps to produce a more effective break, again as the black powder reacts against the force surrounding it.

PASTING

Pasting provides a "shrink wrap" covering for the entire shell. Pre-cut pieces of craft paper are covered with paste and wrapped around the shell. This first wrapping, or "band", does not completely cover the display. These shells are put in drying racks and left to dry, which may take 24 hours or more depending on the amount of wrapping and weather conditions. Drying can be done outside when weather permits or in heated indoor rooms. When the first wrap is dry, a second, larger sheet of paper is covered with paste and wrapped around the shell. This sheet, called a cover, completely surrounds the shell and is tightly twisted around the fuse to prevent accidental ignition. The shell is wrapped again with a final wrap, which is crumpled up to break the grain of the paper, causing the cover to dry tighter on the shell.

At this point, magazine storage is required if work is finished on these materials for the day. If special fireworks, even pasted fireworks in the process of drying, are kept in process buildings overnight, a variance must be obtained. This variance requires that the process building meet all table of distance requirements for the quantity of material being held. The variance does not require that the process building meet all magazine construction requirements.

FINISHING

After the shells have dried, they are taken to a process building for fusing and final assembly. The fuses, which ignite the lifting charge as well as the break charge, can be made at the fireworks plant or purchased. The external fuse, or quick match, is made of a cotton string coated with black powder and covered with a paper tubing. This covering retains the gases from combustion and produces an extremely high burn rate of approximately 60 feet per second, much higher than if the fuse was uncovered. In this example, you can see that the uncovered fuse burns at about the rate of 1-2inches per second while a similar length of covered fuse burns much quicker. The internal time fuse, on the other hand, used to provide a precise time delay between launching and explosion high in the air, burns at a rate of approximately 2-1/2 seconds per inch.

The quick match fuse is attached to the side of the shell, and outer covering of paper is applied, creating a pocket on the bottom of the shell for the black powder lift charge. Sometimes this pocket is made of aluminum foil which provides better protection against accidental ignition or water damage. A specified amount of powder is poured into the pocket, depending on how high the display is intended to be fired. The quick match fuse enters this lift charge pocket and has been connected to the timing fuse of the burst charge. The other end of the fuse is covered with a safety cap to prevent accidental ignition.

This cap is only removed just prior to firing the shell. The edges of the pocket are folded up and fastened, in this example with string. Because the shells are lowered into the mortars by their fuses, larger shells have string handles attached to them for lowering, as the fuse is not strong enough for this task. The outer wrapping is now marked with the ATF required markings including the manufacturer's name and address. There should be a date shift code which will specify when the shell underwent final assembly as well as a label identifying the type of shell. This is now a completed special firework. Finished aerial shells are spherical or cylindrical in shape with a paper or plastic exterior. They typically range from 2 to 12 inches in diameter, although larger sizes are occasionally used.

STORAGE

Explosive mixtures, explosive components, and finished special fireworks must be stored in an appropriate magazine unless they are being assembled, packaged, or transported. ATF realizes that the less materials are handled, the safer they are. For this reason, ATF may grant variances which permit products to be moved less frequently in and out of magazines.

Most special fireworks are classified as low explosives and may be stored in a type 4 magazine. These magazines, like the ones illustrated, may be of masonry construction. The walls and floor must be of a non-sparking material or lined with non-sparking material or lattice work. The doors are to be constructed of metal or solid wood covered with metal. The hinges and hasps must be welded to the door. Two locks are required and can be of the padlock or mortise types, as seen here. Remember, when unlocking a magazine, be sure to check the hoods for biting or stinging insects. The ground should slope away for drainage purposes and there should be no debris or flammable material around the magazines. The Table of distances for the storage of special fireworks (except bulk salutes) is contained in the ATF regulations. The table provides the separation distances between magazines, magazines and inhabited buildings, passenger railways or public highways for the amount of special fireworks contained in these magazines

Flash powder and bulk salutes however, are classified as high explosives and must be stored in type 1 or type 2 magazines. These magazines must be of masonry or metal construction. Floors must be of non-sparking material. Doors which are made of 1/4 inch steel must be lined with at least 2 inches of hardwood. The hinges and hasps must be welded, blind bolted, or riveted to the door. The magazine must be bullet resistant and have adequate drainage and ventilation. Two locks must be used which can be any combination of hooded padlocks or mortise locks. If two mortise locks are used a different key is required for each lock. These type 1 and type 2 magazines must meet the table of distances for storage of explosive materials contained in the ATF regulation.

Chemicals used in the manufacture of fireworks should be stored separately from the finished fireworks. Until they are combined, these chemicals are not explosives and as such are not required to be stored in a magazine. The black powder used in the manufacture of fireworks is a low explosive however, and must be stored in a type 4 magazine. It too should be stored separately from other components.

SUMMARY

This video has provided you with an introduction to fireworks manufacturing methods and ATF's regulations covering the fireworks industry. By establishing requirements for proper storage, appropriate separation distances, and powder limitations in process buildings, ATF strives to enhance the safety of this American tradition.

Our thanks to the American Pyrotechnics Association and Zambelli Fireworks Manufacturing Company for their generous contributions of effort and the use of their facilities in the development of this video.

THE DEVELOPMENT AND APPLICATION OF FIREWORKS STANDARDS IN THE UNITED KINGDOM

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ABSTRACT

The paper describes the development of the British Standard for fireworks, its main features and application, the ensuing work in Europe and the prospects for an international ISO standard. The emphasis in the BS is on performance assessment supported by on-going quality control sampling. Manufacturers and importers are required to carry out their own testing with spot checking by enforcing authorities. The UK initiated the European (CEN) Standard work in 1989 and whilst good progress has been made on general issues wide variation in the requirements for individual types has been found. These arise largely through the different customs and practices in individual European countries. No doubt the differences would increase if an ISO standard was to be developed, and consequent delays in their resolution would have to be balanced against the advantages of harmonisation and increased pressure on removal of unsafe fireworks worldwide.

INTRODUCTION

Legislative Control

The two main legislative requirements covering the availability of fireworks in the United Kingdom are The Consumer Protection Act 1987 and The Explosives Act of 1875. The former covers the safety of fireworks when sold as consumer goods to the general public, usually through retail outlets such as shops and newsagents. The latter is the main legislation under which all explosives are authorised for general sale. The Explosives Act is a relevant statutory provision of the Health and Safety at Work Act 1974 and as such is primarily concerned with work activities.

All fireworks in the UK have to be both authorised for general sale, in which their safety when used is considered, and classified in accordance with the UN scheme for transport, storage and supply. Furthermore all fireworks require a licence prior to their importation.

Need for Change

During the 1980s the UK experienced a dramatic increase in importation of fireworks particularly smaller, commonly referred to as shopgoods, fireworks from the Far East. The procedure at that time was for the Government Competent Authority the Health and Safety Executive (HSE) to take small samples of individual items and test them prior to authorisation. The tests had been developed by the HSE for their own purposes and were not available to others. As the variety of firework types and sources of supply grew it was realised that this system did not work too well - it lacked consistency, did not consider quality control, and the testing by competent authorities did not encourage the industry to undertake the assessment of their products. Indeed it could be argued that it took over the responsibility placed on companies to ensure the safety of the fireworks they supply.

DEVELOPMENT OF A BRITISH STANDARD

With these considerations in mind in 1984 the HSE prompted the commencement of work on a British Standard. The committee responsible had members from industry, consumer safety groups, and firework users representatives as well as government agencies. This rounded consultative approach was believed to be the best way of achieving consensus.

In November 1988 The British Standard for Fireworks (BS 7114) was issued and in March 1989 it was approved under the Consumer Protection Act by the Government Minister concerned with consumer affairs. It applies to all fireworks for entertainment both UK manufacture and imported. The licences for imported fireworks now have a term requiring compliance with the standard.

Structure of the BS

The standard classifies fireworks into four different categories according to their use and hazard:

Category 1 - indoor types
Category 2 - garden types
Category 3 - display types
Category 4 - professional types.

The document is very comprehensive describing all the individual types available in categories 1-3. It specifies the dimensions and performance criteria, labelling, sampling and a detailed description of the tests. The emphasis is on safety in use and the tests are mostly concerned with firework performance. It is not concerned with UN classification for transport. A main feature is the requirement for on-going quality control and testing of each batch produced. Having the tests clearly described allows the manufacturers or importers to arrange for testing themselves, and releases enforcing authorities to audit and monitor the quality of goods on the market.

APPLICATION OF THE STANDARD

Importers and manufacturers nominate their test laboratories to the HSE who visit the site to assess suitability and provide guidance. A formal accreditation or approval scheme for competence of test sites to undertake the work is not operated. The system is supported by monitoring of fireworks on the market by Trading Standards Officers in various regions around the country, and by Explosives Inspectors during visits to licensed factories and magazines.

The system has now been in operation during three firework seasons in the UK. It is accepted by industry as a valuable aid in improving firework safety and, whilst it is too early to make detailed statistical analysis, appears to have contributed towards reducing the number of accidents in the smaller shopgoods end of the market. Certainly most of the dangerous and unreliable fireworks that grew in number during the last decade are no longer available.

EUROPEAN WORK

Background

After completion of the British Standard the UK initiated work on a CEN or European Standard in 1989. We looked ahead towards the single market due to commence in January 1993 and saw that there was a lack of consistency and standards across Europe - each country had its own controls, systems, and standards. We were concerned about the effect across the Community with all barriers to trade removed and the possibility that items freely available in one country should be freely available in all. Clearly other countries had similar concerns shown by the voting which resulted in the vast majority positively in favour and only one country against.

The work did not result from a specific EC Directive on fireworks. However it is understood that such a Directive is under consideration and might refer to the CEN standard. Work on a general explosives Directive excluding fireworks commenced in December 1991.

Progress in CEN

Detailed commentary on specific issues in the CEN standard are being presented at the symposium by Mr R Rapley. It is the intention in this paper to present a personal overview of the experience so far and what an international audience might consider when debating widening the work beyond Europe.

Good progress has been made on general issues within the standard given the considerable variation in use and availability of fireworks between the different member states. Countries have been prepared to compromise on established positions. Agreement has been reached on the classification of fireworks, again, as with the BS, into four categories. A major breakthrough was the acceptance of batch testing as well as type testing with agreed sampling levels. Recently progress has been made towards accepting testing distances which demarcate the different categories.

The approach to acceptance of individual types within each category has been to list all those currently available in the different countries. The intention is that each country will be able to ban individual types as it sees fit. For example the UK and Netherlands do not permit items of erratic behaviour such as jumping crackers and wish to continue to do so. Final agreement on the mechanism for implementing this system has yet to be achieved, and it may well be a political matter outside the remit of the CEN committee.

Customs and Practices

When, however, detailed specifications for individual types have been addressed progress has been slow. The first type to be considered, bangers, has revealed the wide differences on firework acceptability from country to country. The problems essentially are derived from variations in custom and practice and are not straightforward safety issues.

The main difficulty with fireworks is that their availability is closely tied in with history and tradition, more so than for most other items such as electrical equipment or other modern goods. Legal controls also are approached differently. For example in the UK it is against the law to set off fireworks in the street or to throw them, most are set off in gardens hence our name for category 2. In some other countries the practice is to, legally, set them off in city streets - in Germany for example during a short period on New Years Eve. Different traditions have evolved and influence the explosiveness of the fireworks generally available.

To illustrate this point Table 1 shows the differences between countries on banger explosives content and type. The argument as to whether flash composition (potassium perchlorate/aluminium mixtures) should be allowed has been resolved by creating a different individual type to be known as a flash banger. The differences in explosive content, however, remain considerable and so far unresolved.

Another example is in Table 2 which shows the response from different countries in respect of rocket content. These differences may pose less of a problem than those with bangers but illustrate again the considerable variation between countries.

Entertainment and Safety

Process towards reaching agreement is affected considerably by the potential conflict between the entertainment aspects of fireworks and their safety. The public likes the fun side but of course wishes to avoid accidents. People in countries with a tradition of loud banger availability may well not take happily to a reduction in their power, whereas those in a country used to having only weak types would be extremely concerned at the prospect of increased accidents that would be likely to ensue from larger bangers. In the UK firework accident statistics have been produced for many years and the decision to reduce banger size was taken when they were seen as a source of accidents. The action did lead to a reduction in injuries.

There is therefore the essentially political debate of balancing entertainment with safety. To what extent should fireworks be banned in a standard? Should it just cover warning and specifying, allowing the individual country or indeed member of the public to decide, or should the standard be more interventionist forbidding certain types?

The approach taken at CEN appears to be the best way forward. That is to specify all types available on the different markets, defining tests and criteria, labelling, and most importantly quality assurance procedures as part of production and distribution. But leaving the banning of certain types to political decisions within individual countries.

ISO STANDARD

The subject of an ISO has been raised at the OECD-IGUS meetings. There would be undoubted benefits in removing unsafe fireworks from the world market. The high volume producers would be encouraged internationally to improve quality and produce fireworks to a more reliable higher specification. Furthermore the worldwide market that exists in firework sales, particularly from the Far East to Europe or America, lends itself to developing such a standard.

These advantages have to be set against the likely magnification of the custom and practice difficulties encountered in Europe. There are even greater differences in firework availability and use between the Far East, America and Europe than there are between individual European countries. Whether these are resolvable without unacceptable dilution of the standard is open to doubt. They would almost certainly lead to considerable delays.

The timetable for producing the CEN standard has already been extended twice. The second date has yet to be formally ratified at the plenary meeting in Madrid in June, but it now looks as though completion of all items will not be before 1997, a slip of four years from what was envisaged at commencement.

Consideration of an ISO standard has to be set against the above background and the European experience so far. Nevertheless the potential rewards make it a topic worthy of further exploration.

TABLE 1

BANGER EXPLOSIVE CONTENT

Country	Category 2		Category 3	
	NEC (g)	Substance	NEC (g)	Substance
UK	1.6	BP	10	BP
Germany	10	BP	25	BP
France	10	Flash	15	Flash
Netherlands	2.5	BP	-	-
Spain	4	Flash	15	Flash
Sweden	0.8	BP	-	-
Finland	15	BP	15	BP
Italy	10	Flash	20	Flash

Notes (Tables 1 and 2)

1. NEC = Net Explosive Content.
2. BP = Black Powder as defined for UN No 0027.
3. Flash or F = mixture of potassium perchlorate and metal powder usually aluminium
4. The information was collected from delegates responses during CEN discussions and is not an authorative statement on countries positions.

TABLE 2

ROCKETS EXPLOSIVE CONTENT

Country	Category 2 NEC (g)		Category 3 NEC (g)	
	Total	Report	Total	Report
UK	60	-	250	-
Germany	30	10 (BP)	75	-
France	100	-	500	-
Netherlands	25	4	-	-
Spain	100	0.5 (F)	75	15 (F)
Sweden	100	3	300	-
Finland	100	-	300	-

METHODS AND EFFECTIVENESS OF FIRE PROTECTION SYSTEMS IN FIREWORKS MANUFACTURING FACILITIES

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ABSTRACT

Due to the nature of the product and the seasonal aspects of most firework manufacturing, there is always the danger of fire and explosion. Many hazards can be eliminated by methods as simple as improved housekeeping and separation distances. Since most fireworks manufacturing operations are affected by the seasonal sales cycle, we see increased occurrences of accidents during the preseason production efforts. This is understandable due to the increased quantities, the possibility of less experienced, newly hired personnel and in many cases, less attention to housekeeping and/or safety. The remedy to many of these problems may be as simple as modifying production or storage methods and employee safety training. There are some manufacturing operations where the chance of fire or explosion is unavoidable.

Although the chances of something going wrong are rare, it is often just a matter of time and circumstance. Our discussion will introduce the option of incorporating state-of-the-art, active fire suppression systems in the manufacturing operation. We will look at the effectiveness and cost of such systems presently used in military pyrotechnic and explosive manufacturing.

INTRODUCTION

The manufacture of fireworks presents unique hazards and challenges for companies and individuals concerned with property and life safety. It is fair to say that the manufacture of fireworks is more dangerous, than the production of many of the military ordnance items in use today. Fireworks, because of the multiple and varied effects required, have many different pyrotechnic mixes in one device. Fireworks may contain a combination of two or more of the following; star mixes, black powder, starter mix, flash, delay mix, burst charge and possibly devices within a device. It is very rare for a military device to incorporate such a variety. From a fire hazard standpoint low explosives and pyrotechnic mixes, more common in fireworks than in military ordnance, are much more dangerous than high explosives. The fireworks production technician must be trained and set-up to work with this large variety of product, where a military technician may only work with one product (propellant, smoke, flare, etc.) during his career.

North American fireworks plants have a good safety record, (sometimes marred by accidents at illegal operations) this record can be maintained and improved by simple safety practices ("passive fire protection"). In addition, High Speed Deluge ("active fire protection") can be used in critical operations.

Passive Fire Protection

Fortunately some of the best methods of fire protection are also the least expensive and most obvious. During the manufacturing and process of high energy chemical mixtures, fire safety can be approached with two thoughts in mind, first is to reduce the chance of ignition and second is to reduce size of fire or explosion if ignition does occur.

The most dangerous phases of the manufacturing process are probably the mix/blend phase, consolidation/press/forming phase and the drying phase. These operations have the advantage of being capable of modification to lessen the chance of ignition. Ignition will occur when there is enough energy input to start the chemical reaction. This energy can be introduced by heat, impact, friction, pressure, static and chemical reaction due to the use of incompatible components.

Static is most prevalent in dry weather. Static can be caused by movement of objects including people. Pouring liquids, powders and granules can produce large amounts of static. Being conscious of the existence of static, grounding methods and developing static defeating work habits is a very good defense against static hazard. Provide plenty of well labeled and accessible ground bars along with instilling work habits that will encourage their use.

Static hazard is a science in itself and cannot adequately be addressed in the scope of this paper. Static is worth further research for any individual working with high energy chemical mixtures either as a professional or hobbyist.

Friction, pressure and impact are categorized together for the purpose of this paper even though each has unique definitions. Friction can occur between any two surfaces that can range from a mixing blade and mixing bowl to friction between two chemical granules. Process equipment and tools can be modified in ways to reduce the chance of impact and friction. Simple methods such as tethering scoops and tools so they cannot be dropped into process vessels or the wrong containers and eliminating loose or unnecessary tools and personal items in the work area, are just a few of the simple and inexpensive methods to reduce accidents.

Avoid friction between finished products. For example, place products on a tray versus dumping them into a bin. Keep process equipment in good condition, loose bearings can cause a mixing blade to impact a mixing bowl, a loose screw can jam and spark in process equipment. Loose parts and panels can be a source of vibration, an area for explosives to collect or a pinch point that could be a source of ignition. The mix blend operation can be made less ignition prone by the following methods:

* Use static and spark proof tools.
* Ground personnel, work table, tools and mixing vessels when possible.
  (When using direct body ground on personnel be sure to use series resistor to safeguard against electrocution.)
* Use the safest and most compatible chemicals that will do the job.
* Use the best quality chemicals.
* Use separate scoops, sieves, and measuring devices for fuels and oxidizers.
* Keep quantities as small as possible.
* Use the most gentle mix/blend method that will provide the required mixture intimacy.
* Use the smallest possible distance when pouring mixtures.
* In most cases add the oxidizer(s) to the mixture last.
* Maintain good housekeeping.
* Keep equipment "tight" (no loose bearings, parts).

Consolidation, press and forming operations can be made safer by incorporating simple changes in the process. The following is a partial list of hints representing just a few methods, as common sense and thought will reveal many more:

* Keep consolidation pressures as low as possible.
* Keep pre-consolidation material to a minimum.
* Avoid stockpiling of finished product in this area.
* Keep dies in good order.
* When rolling stars keep belts, tumblers, well grounded.
* Close or remove any solvent not in use.

Drying operations are basic in nature and there is not a lot that can be done, other than the obvious to keep drying as safe as possible. The following are a few suggestions:

* Be sure the chemicals being used are compatible.
* Use correct amount of liquid as binder solvent.
* If using an oven, be sure the heat source is free of sparks and flame.
* Keep quantities as small as possible.
* Dry in remote location.
* Avoid friction and movement during drying operation.
* Be sure evaporating solvents cannot come in contact with spark or flame.
* Use as little heat as possible to do the job.
* Know the sensitivities of the product.
* Watch for liquid migration or abnormal crystals on product during drying.
* Maintain good housekeeping, clean dust and "crumbs" regularly from drying area.

Housekeeping, separation distance and batch size monitoring are the simplest and least expensive methods of fire protection available to the fireworks production facility. Eliminating build-up of hazardous material is a very important aspect of housekeeping. One method of controlling build-up on hard to reach corners and crevices is to use silicone caulk on trouble areas in the process room and machinery. Fires often propagate along the path of excess powder left behind because of poor clean-up procedures, this is another reason to keep in process quantities to a minimum in case of such propagation. Vacuuming of explosive material can be very hazardous due to the static build-up as the powder moves through the hose. The accumulation of explosive in an enclosed container, the possibility of dust getting into the moving parts and the probability that the electrical rating of the equipment does not meet the explosive atmosphere requirements. If using hose-down method of clean-up, beware of the type of sediment and the location of sediment buildup that often happens during wash-down.

Electrical equipment and fittings should meet the requirements of the electrical code for the hazard in the area. Electrical equipment and fittings should be kept in good repair, especially where solvents are being used. Pyrotechnic fires have been started by solvent creeping into an area where a spark is present and the solvent fire propagates to the pyrotechnic mix.

Separation distance and batch sizes should be balanced to allow for adequate production and maximum safety. The temptation to increase batch size or lessen separation distance because of increased production requirements should be avoided at all cost. The simple action of covering a batch or product container can prevent the ignition of large amounts of product in the case of a flair-up. The production increases that sometime come with seasonal demands or deadlines may require hiring of additional personnel. Special attention should be given to safety training and making them aware of the logic behind such rules.

Employee safety training is essential. Since most accidents are the result of human error it is obvious that employee training is the most important part of your safety program. As mentioned previously, it is important that the employee understand the reason and logic behind the safety rules. This is the only method by which they will learn and follow rules. A person who handles and works with high energy chemicals should have a respect for the product but not a fear of the product. One of the most effective ways to instill this respect is to allow the employee to witness the effect of the product when ignited. A worker involved with quickmatch or makes set pieces should be given the opportunity to witness the burning of quickmatch. The same goes for star mix, black powder or any other product. By knowing what to expect in the rare occurrence of ignition, the employee can plan an escape and course of action...they should always have a plan of egress in mind. When performing routine tasks it is easy to become lax, even when working with explosives. All personnel should watch for and be alert to this.

It cannot be emphasized enough that the employee must understand the reason and logic behind a particular rule. By handing a person a sheet of paper telling them not to wear nylon panties, jewelry or synthetic fabrics will not be as effective as explaining that these fabrics cause static and jewelry can spark or fall into process equipment. Learning is always preferred over memorization.

"Passive fire protection", though literally speaking is not passive at all, is the least expensive and most effective method of fire protection that a fireworks manufacturing facility can implement. "Active fire protection", for the purpose of this paper can be defined as a fire protection system that is designed for and dedicated to the task of suppressing a pyrotechnic, explosive, or high energy chemical deflagration.

The following will address the effectiveness and typical applications of High Speed Deluge systems.

Active Fire Protection

The typical fire protection system, known as wet pipe and dry pipe systems, are common in many buildings ranging from warehouses to motels. One of the few structures where this type of fire protection system probably does **not** belong is in the fireworks production facility. This type of system has a reaction time of several seconds to minutes. This is too slow to be effective in suppressing a deflagration in high energy chemical facilities...it would be a waste of effort and money.

High speed deluge systems are common in government and military facilities that process explosives, pyrotechnics and munitions. The definition of a high speed deluge system is a system that has a reaction time of 100 milliseconds or less. These systems utilize optical fire detection that allows for fast detection of flash or flame. In most cases high speed deluge can suppress a deflagration before it reaches dangerous proportions or possible detonation (in the case of high explosives).

Water is used as the extinguishing agent, there is a good reason why something as basic as water is used over the many extinguishing agents available. The fire triangle that is familiar to all of us requires three components to maintain combustion; fuel, heat, and oxygen. Pyrotechnic and explosive mixes contain oxidizers (nitrates,chlorates,etc.) and do not require "air" to burn. The only way to stop deflagration of these mixtures is to cool and disperse the mixture. Water has proven to be the most successful agent.

The speed necessary to halt a pyrotechnic deflagration is dependent on many variables including the type of process (whether it is an enclosed vessel, an extrusion process, mixing, drying, pressing, etc.) and the proximity of the personnel and critical equipment. There are some cases where the only alternative or option is to allow it to burn. Conversely, there are instances in which high speed deluge is necessary to save lives and protect costly equipment.

Some factors that may influence the speed of deflagration are, mass of the compound, density, temperature, moisture or solvent content, the physical geometric shape or particle size of the compound, and whether or not the substance is contained. A good example of how different containments could affect the burning characteristics of high energy mixtures is that of black powder. Black powder, one of the oldest and most versatile explosives, when burned in an open long train is relatively slow burning and is sometime used to make fuse. Confined in a tube with one end open for exhaust black powder can be used as a propellant. When confined in a fairly rigid vessel, black powder can become explosive with deflagration speed almost reaching detonation.

As we mentioned earlier High Speed Deluge is used extensively in military munitions operations, they use large amounts of high explosives and propellants and a lesser amount of pyrotechnics. Fireworks on the other hand require more pyrotechnics than propellants and high explosives. We will discuss some propellant and explosive applications but stress pyrotechnic fire suppression.

The following are a few basic guidelines for designing a High Speed Deluge system. For the sake of clarity, energetic chemicals are broken down into three (3) basic groups. The categories are High Explosives, Pyrotechnics/Low explosives and Propellants. Some of the following text that deals with military explosives is from one of my previous papers.

High Explosives

Often, the first thoughts or reactions to high speed deluge protection for high explosives is, that there is no fire protection system that could stop the detonation process when the explosive goes to a high order state and this of course is very true. But, in many cases prior to the explosion, there is a fire. Examples of high explosives process applications are extrusion dies for C-4 explosives or a TNT melt kettle. In these situations, there is a good chance that there will be a fire preceding the explosion. The fire could start and propagate until the pressure build-up was enough that we achieve high order detonation or in other words, a cook-off type of reaction. In this situation high speed deluge would be quite feasible in stopping the initial fire which precedes possible explosion. Again, dealing with high explosives the processes must be considered. For example, a TNT melt kettle is a closed vessel with a steam heat jacket, in most cases, operating at approximately 180 degrees Fahrenheit. Often the enclosure is operated at a slight vacuum. One way to attack the situation is to provide infra-red detection within the melt kettle. With this in mind, infra-red flame detection at the present state of the art is susceptible to ambient light. Design consideration should be made to disable the infra-red detection when the melt kettle is open either for cleaning or for adding material. Infra-red detection is less susceptible to the attenuation due to dirty lens caused by steam, smoke or particles than it's ultra violet counterpart. So, in this case, infra-red detection lends itself to a fairly good design option. Also, in the case of a TNT melt kettle, flooding of the kettle with water is necessary. There is no need for special spray nozzle patterns in this situation. The objective would be to get as much water as possible into the kettle for the flooding action to extinguish the fire. Deluge speed in this case is essential, due to the fact that we have an enclosed vessel and a fire situation could build pressure rapidly in the vessel, possibly to a point high enough to cause detonation. One other option for melt kettles may be quick release venting, either mechanical gate or rupture disc method. Recent study has shown that a detector within the melt kettle will only see surface flame and there is a good chance that the fire will start at the bottom. In view of these new facts it may be advisable to protect the operator as he fills the kettle with external UV detectors and eliminate the internal detection, one should consider their options.

A common process in high explosive product manufacture is casting. Oftentimes TNT, RDX or HMX type materials are casted into a shell, bomb, or a mine housing. In this process we have a molten explosive being physically poured into a chamber. There is a chance for spilling or overflow and there is exposed explosive often from the ejection point to the fill area. For casting and filling, ultra-violet detection with high speed deluge nozzles as close as possible to the hazard are recommended. Since ultra-violet detection is not susceptible to normal ambient light, it would be the least troublesome and beneficial type of detection, again, bring your nozzles as close as possible to the hazard.

Extrusion is a process encountered with explosives. For instance, extruding C-4 explosive blocks. One possible source of fire is at the extruder die. As the explosive leaves the extruder die, there is often friction and the explosive is under pressure making this a likely ignition point. Ultra-violet detection, with nozzles as close to the hazard as possible would be a viable method to help prevent an incident.

High explosive melt-out or steam-out is a common application for high speed deluge. The design would have to vary with the particular process involved, which is actually more dependent on the munitions involved in the meltdown. A demil (demilitarization) process often encountered is the belt flaker or "candy maker".

In the belt flaker the high explosive, often TNT or RDX is melted and extruded onto a stainless steel water cooled conveyor belt. As the conveyor moves along, the explosive solidifies and breaks off at the end and is either boxed or sent on to other processes. Detectors (ultra-violet) should be placed within the conveyor hood. Nozzles are installed within the hood as close as possible to the hazard.

Because of the presence of steam and vapors, it is recommended that air shields are used to keep the detector lenses clean and maintain the system's integrity.

Pyrotechnics/Low Explosives/Fireworks

Design considerations for low explosives will be combined with pyrotechnics, since many of the methods for detection and suppression are the same. Items that fall into the low explosive and pyrotechnic category are golden powder, black powder, illumination flare mixtures, mag-tef flare mix, smoke mixes, first fire, delay mixes, fireworks, salute mixes, etc. A few of the processes involved in the manufacture of low explosives included grinding mixing, activation of binders, extruding pressing, granulating and drying, these being some of the most common processes encountered.

The initial grinding process is probably the least hazardous due to the fact that, in most cases, the ingredients are still separated. For example, the oxidizers should be ground separately from the fuels. Processes such as roll milling or ball milling demand customized systems designed on a one-to-one basis. Each situation is unique and should be handled accordingly. Often encountered during pyrotechnic production is the use of solvents to activate binders. Solvents, are in most cases, flammable with flammable vapors. To compound the problem, certain vapors attenuate U.V. radiation emitted from the flame. The characteristics of the solvent must be determined along with its effect on the detection system. In past explosions the flammable solvent fumes were in some cases, the initial source of fire that then propagated to the pyrotechnic mix. Even though as a rule, solvent dampened compounds are less sensitive than dry, the problem of the flammable solvent fumes must be considered.

Grinding and granulation is a hazard because we are exerting extreme physical forces on the completed pyrotechnic mix. Chances for impact, friction and even static initiation is much greater at this point. Compounding the hazard during this step of the process is the fact that we are working, in most cases, with large bulk amounts of the product. When protecting a container or hopper with large amounts of pyrotechnic product, it is recommended that the system not only applies water from the top but also provides for flooding of the vessel from the bottom or the sides.

Composition pressing is a very common practice in pyrotechnics, especially in the case of smoke and flare compositions. During the pressing procedure, the pyrotechnic mixture is compacted at very high pressures exerting large physical force, up to thousands of PSI.

Although it is almost impossible to stop any ignition or deflagration in the press or the object being pressed, it is often advantageous to suppress propagation of the flame or explosion to bulk hoppers containing mix yet to be pressed into the finished pelletized product. Often the pressing machinery is designed and shielded to withstand initiation during the pressing procedure. In this situation, the objective would be to protect operators and counter propagation.

Application of "first fire" mix is a fairly dangerous task and often involves an operator in intimate contact with the hazard. The operator is working with a sensitive mixture, even though the mixture is wetted.

If the first fire were to initiate, it could cause initiation of the parent product. One example would be the application of first fire to magnesium teflon flares, if done manually, the operator is directly exposed to the high temperature burning of the magnesium teflon flare. In this scenario, one option is to aim the fire suppression nozzles at the operator and also use nozzles configured to drive the burning flare into a hopper or chute so that it is driven away from the operator. The reason being that certain compositions, including magnesium teflon, mixes are very hard to suppress with the water spray, so it is best to separate the operator from the hazard.

Usually, the final stage in the production of a pyrotechnic mix is the drying phase. During this phase the solvents are removed from the final product or the product is allowed to cure. During the drying process the pyrotechnic mixture is often subjected to added heat to facilitate faster and or even drying. At this point, the pyrotechnic product is susceptible to ignition. Ignition may be due to spark, friction or impact but is sometime due to a chemical reaction during the drying process. In many cases this is an unpredictable reaction. High speed fire suppression is a very good safety measure unless the cost of the product loss is low enough and equipment is built to withstand ignition. Then it may not be economically feasible to use high speed fire protection unless of course operators are exposed to hazard.

Frequently, fires occur during cleanup or equipment tear-down. This should always be considered when designing an explosive prevention system or high speed deluge so that the system will activate and do its job during the cleanup and tear-down process if it is deemed a possible hazard. In most all cleanup or repair situations, plant personnel are in the hazard area where explosive residue is present.

Propellant

Propellants offer some similarities in reference to hazards that the explosive and pyrotechnic categories present. However there are some processes that are unique to propellant. Propellants are extruded, which offers the same hazards as extruding high explosives, except for the fact that, in most cases, propellants will burn much more aggressively, although there is probably not as much of a chance of achieving detonation. A good rule of thumb, would be that anywhere there is action (movement, friction impact, static discharge) there is a chance for initiation. In other words, where the propellant leaves the extruder die, or, if the extrusions are being cut into pellets during the cutting action. For composite propellant mixing, high speed fire protection flooding of the mixing bowl is advised. If using a closed mixer, infra-red detection is presently the state of the art method to use in the closed vessel. It offers faster reaction time and is less subject to blinding or obscuration.

Sometimes propellants are machined after casting or pressing. The propellant machining process should be monitored by ultra-violet type detection keying where the tooling comes in contact with the propellant and if operators are present, protect the operator, stop propagation to hoppers or to propellant feeds. Often the propellant pellets, especially the nitrocellulose type propellants, are coated with graphite to help its flow through processing equipment and to prevent possibility of static discharge.

The added graphite coating can cause two potential problems. (1) It can obscure the detector lens because it has the tendency to float in the air and (2) it can inhibit deluge water penetration into the propellant mix due to its ability to shed water. In the case of graphite coated propellants it may be advisable to use air shields on the detectors and provide penetrating and flood type spray configurations.

Propellants are often involved during demil (demilitarization) operations. During the demil process the munition body is separated or opened so the propellant may be poured into a collection container. The equipment, and operator if present, should be protected during the step when the projectile is pulled from the shell or cartridge. Also, during the pouring of any propellant, there is a potential hazard because of friction and possible static initiation. There is also a chance, due to the age and storage condition, that the propellant may have become more sensitive than normal. Large quantities of propellants when contained in hoppers or similar containers should receive deluge water both from above and flooding from within the container as with some of the pyrotechnic mixes.

The nature of the progressive burning and increasing burn velocity of propellants emphasizes the need for a very fast fire protection system that will extinguish or suppress the flame before it can get to the point where it is out of control and the gas velocity is such that it will not allow for water penetration.

"Thermal dehy" during the propellant manufacturing process is another feasible and recommended application for high speed deluge. In this case, if hooded equipment is involved, infra-red detection is probably the best answer.

Triple base propellant (consisting of nitrocellulose, nitroglycerin and nitroguanidine), double based propellants (consisting of nitrocellulose and nitroglycerin), single base propellants (consisting mainly of nitrocellulose), do not exhibit different characteristics as far as the ability to be extinguished by water spray, although the burning rates and temperatures do vary. More testing would have to be done to verify the affects of the water spray (varying amounts and speed) on the different propellants. So far, water has proven to be very effective when delivered quick enough. Composite mixtures, i.e. ammonium perchlorate and aluminum can be protected during the pour and casting process and during the mix process. The system configuration would have to be determined specifically for the process.

Initiating explosives such as mercury fulminate, lead azide, lead styphinate, pose particular hazards due to their combustion characteristics. They are very sensitive to heat, static, friction and impact initiation and they seem to transcend the deflagration state and almost evaporate into a detonation. With these compounds, probably the wisest safety measure would be small batches and isolating the material. High speed deluge for these initiators would probably only be effective as a deterrent to propagation. Avoid using brass fittings and nozzles in lead azide areas as copper and brass, when combined with moisture, may cause lead azide to form extremely sensitive copper azide.

As previously stated, general overall coverage type systems located high in the ceiling, should be avoided, but as with all rules, there is an exception. The exception being, that, in an explosive area where there is chance of dust or explosive particles which had previously settled on equipment or parts of the building, a general coverage high speed deluge may help to eliminate the explosive hazard. Good housekeeping and a cleaner working environment would probably be a more cost effective way to handle this problem.

If there is a chance of secondary explosion, i.e., an initial blast that is hopefully suppressed by the primary system, were to force out explosive dust or particles allowing for a secondary explosion, a secondary overall coverage system may help to eliminate this.

The preceding was a brief summary of a high energy process applications where high speed deluge may be incorporated. There are many other substances and processes that warrant the use of high speed fire protection, this has been a review of some of the more common. It cannot be stressed enough that, both the substance and the process should be reviewed before designing and installing a high speed fire protection system. Specifications for the systems should be written per the application. More times than not, generic specifications do not provide for a system that would do the job adequately.

Whenever possible, it is suggested that actual burn tests be performed using the same high energy substance and the same process situation for the test and design as will be used in the final application. When in doubt, the best rule of thumb is to use common sense when designing your systems and to have intimate knowledge of the product and process involved and do as much testing as time and budget will allow.

Portable High Speed Deluge

Having quickly covered some fixed high speed deluge applications, it is appropriate now to introduce a new concept in high speed deluge for high energy chemicals, the Portable High Speed Deluge System. It is hoped that Portable High Speed Deluge could prove to be a viable life safety system, and at the same time provide cost savings, in certain unique applications. Portable High Speed Deluge is a totally self contained fire detection and suppression unit. Totally self contained meaning; battery power supply to provide power to detectors and to activate the system; self contained water supply and pressurizing capabilities to propel the water; and the ability to move not only the portable unit itself but also reconfigure and relocate the detectors and the nozzles. The Portable Deluge System should be able to achieve reaction time of at least fifty (50) milliseconds. Reaction time defined as: time from instant of flame detection to flow at nozzle. The batteries should provide power to the unit for at least eight (8) hours and be supervised to signal and annunciate the loss of power. The system should be completely supervised for detection, solenoid integrity, loss of pressure, low water, and any other function that might inhibit the system's operation.

The Portable System is not intended to replace or eliminate Fixed High Speed Deluge but does suffice in filling the "gap" where Fixed High Speed Deluge is not feasible because of constraints such as water supply and changing processes or where fixed deluge is not feasible for economic reasons.

Listed here are some examples and suggestions where the Portable High Speed Deluge would be advantageous. These are just a few of the many applications where Portable High Speed Deluge could prove useful and cost effective:

* Fireworks manufacturing facilities where the tasks often change and the budget does not allow for a complete fixed High Speed Deluge System.
* Explosive or pyrotechnic spills. The portable deluge could be rolled in and used to protect the area during the clean-up operation, in any area where fire protection may not normally be present.

- When there is not sufficient time or funding to install fixed fire protection quickly enough to satisfy the need.
- Depot re-work where maintenance or operations often change and machinery is involved or replaced by different equipment. In these applications, fixed systems are not practical from an operational, safety or economic standpoint. They may have previously gone unprotected or improperly protected had portable deluge not been available.
- Anytime there is machining, milling, blending or drying, the portable system could be attached to the machinery. This may eliminate the need to move the machinery to a location with fixed high speed deluge; especially advantageous if only needed for a short time.
- When the existing system is shut down and production must go on. Loss of production can be costly, portable deluge may bridge the time involved in getting fixed system back on line.
- Clean up and decontamination operations when equipment is torn down or if there is fear of residual explosives. Clean up can be a most hazardous aspect of tasks at explosive facilities, often exposing operators to unusual and sometime unforeseen risk.
- The portable system would be a very cost effective way to evaluate and test the design of fixed fire protection systems with actual burn test to prove the effectiveness of such systems. The system would allow for easy modification and variations providing more comprehensive test results.
- In research, evaluation and quality control laboratories, hazards often vary as do the processes and material that the technicians are exposed to. Many times the energetic material has known properties such as sensitivity to spark, friction or impact. Sometimes in the case of experimental compounds the properties (possibly hazardous) are unknown. In either case it would be advantageous to be able to roll in a Portable High Speed Deluge System to protect personnel and equipment. Processes in the laboratory environment are also quite likely to change. For example; blending, mixing, granulating, extruding and drying. Changing operations (if hazardous) require an adaptable explosion or fire suppression system. Although personnel are more highly skilled and quantities often much smaller, the explosives laboratory can be a hazardous environment and in some cases warrant the use of such a system.
- Temporary depot and staging areas possibly off-shore or overseas applications. Portable High Speed Deluge can be applicable where fixed deluge could never have been considered possible because installation speed, lack of water supply or varying processes.
- Used in areas were improper or insufficient water supplies are a problem. This would apply to the above mentioned areas (temporary depots and staging areas) and domestic ammunition and pyrotechnic processing plants that have inadequate or no underground supply water supplies in some test areas or building locations.
- Temporary storage protection for in-process work. In the situation of production over runs where surplus must be stored and normal adequate fire protection is not available. Also in the case of rejected production runs, where the product must be stored until it can be reworked or destroyed.
- Portable High Speed Deluge could be an additional backup for existing High Speed Deluge, allowing for inadequately designed systems or unforeseen changes in process.
- Additives can be included with the water supply; for instance, anti-freeze or wetting agents. Water coloring might be added to help evaluate different spray patterns utilizing high speed video (for added clarity). Possible advantages of water gels (sticky water) could be experimented with.

- Portable High Speed Deluge is easy to maintain; it can be moved to a shop or maintenance area for service, allowing it to leave the restricted (hazardous) area. Nozzles with different spray patterns can be adapted, moved and configured depending on operation. Very beneficial for design evaluation for fixed systems. Nozzles may be configured to propel the hazard away from the operator or to push the operator from the hazard with water spray.

CONCLUSION

The average cost of one bay of fixed High Speed Deluge is about US$30,000 installed, a Portable High Speed Deluge System is US$25,000 to US$30,000. A good safety program is the best place to start, High Speed Deluge may be applicable in critical situations.

As one can see in the previous text, most of our work has been done in the military field. We have done some testing with black powder and star mixtures. Because of weather we were not able to run any fireworks related test before this paper was submitted for publication, we hope to have some data at time of the presentation. Pyrotech would be willing to provide personnel, Portable Deluge Systems, and test equipment to any fireworks company that could provide test material and test area. If you are interested in this type of testing please feel free to contact the author.

INTERIOR BALLISTICS OF FIREWORKS MORTARS

by

David E.G. Jones

ABSTRACT

This report describes the use of a ballistics model and computer code originally designed to model the performance of large guns, in order to predict the effect of various parameters on the behaviour of a firework shell in a mortar. The effect of such parameters as mass of the lift charge, mass of the shell and mortar length have been explored and compared with experimental results. The effects of parameters such as friction, leakage area, size and shape of the grains of black powder, which are not easily accessible by experiment, have also been studied.

INTRODUCTION

Interest in the behaviour of fireworks in mortars at the Canadian Explosives Research Laboratory (CERL) is a result of increasing concern by both industry and regulators about safety in the use of fireworks. Additionally, it is part of CERL'S mandate in the realm of investigation of the properties of fireworks under the Canada Explosives Act.

Consequently, a significant number of tests have been performed at CERL on fireworks with the aim of ensuring their safe use. Of importance to these studies are the effects of various parameters on the ejection of fireworks shells from mortars. Among these parameters are the mortar length, the "fit" of the shell in the mortar and the masses of the lift charge and of the shell. Contestabile and his co-workers at CERL have conducted such tests and the results have been described in reference (1). These results, are summarized below under the various parameters studied.

Effect of Mortar Length

In these tests, the effect of varying the mortar length from 56 to 134 cm was investigated. It was observed that the peak pressures were invariant with mortar length whereas both peak-pressure to exit time and exit speed of the shell increased.

Effect of Fit

This effect was studied by varying the ratio $(d/D)^2$ where d and D are the diameters of the shell and mortar, respectively. As $(d/D)^2$ increased, both the peak pressure and exit speed increased while the time from peak-pressure to exit decreased, as expected.

Effect of Mass of Lift Charge

It was observed that both the peak pressure and speed of the shell increased with an increase in mass of the lift charge and the time from peak-pressure to exit decreased accordingly.

Effect of the Mass of the Shell

As the shell mass increased, both the peak pressure and time from peak-pressure to exit appeared to reach minima, whereas, the shell speed decreased.

Purpose of this Investigation

This report will describe the use of a simple ballistics model to treat the interior ballistics of fireworks shells. Shimizu has already developed such a model from first principles (2) and has compared the result of his model using defined propellant grains, with experimental results.

It is believed to be important to determine parameter predictions from ballistic models both for the purpose of comparing with experimental results and for investigating the effect of a number of parameters on the performance of the fireworks shells as well as factors affecting their safe performance in the mortar. The parameters studied here include some of those previously investigated experimentally as well as others. Some of the latter parameters are not easily accessible by experiments. These include the effect of friction between the shell and the mortar, leakage of gas around the shell, the volume available to the gas produced, etc.

BALLISTICS MODEL

The ballistic model has been used by Defence Research Establishment at Valcartier (DREV) to determine the interior ballistics of large guns (3)(4). DREV supplied a copy of the computer code, BALINT, based on this model. The code was written in FORTRAN and designed to run on a Honeywell mainframe computer. It was adapted to run on a PC. In the course of doing so, it was necessary to make some corrections to the code as well as making it interactive. A number of modifications are still required but the results presented here are believed to be as reliable as possible given the variation in some of the parameters, particularly the geometry of the black powder grains.

The model is based on four conditions which yield the following basic equations:

(i) Equation of state of gas from lift charge

$$(P(t)/m)(V(t) - mV) = \text{constant}$$

where P(t) is the pressure of the gas, m is the mass of the lift charge,
V is the covolume of the gas and V(t) is volume available to the gas given by

$$V(t) = V_{ch} + A(s(t)) - m\{1/d + Z(t)[V - 1/d]\}$$

where V_{ch} is the chamber volume (volume under the shell), A is the cross sectional area of the mortar, s(t) is the distance that the shell has travelled in the mortar at time t and the last term expresses the volume occupied by the solid lift charge of density, d, corrected for the amount burned.

(ii) Equation of motion of the fireworks shell

$$dv/dt = (C_f P(t) A \Delta t)/M$$

where, v is the speed of the shell, C_f is the friction coefficient and M is the mass of the fireworks shell. Clearly, the speed, v is directly related to the "friction" between the shell and the mortar.

(iii) Burning rate equation

$$dx/dt = aP^b$$

where, x is the distance that the grains have recessed at time, t and a and b are constants for a given composition of lift charge.

(iv) Form function, Z(t)

$$Z(t) = 1 - (V_{gr}(t))/V_o$$

where Z(t) is the fraction of the lift charge burned at time t, V_o is the initial volume of the grains at time t. Z(t) is a specific function of size parameters for each type of grain geometry. Therefore, it is necessary to make an assumption about the size and shape of the grains in the lift charge.

Table 1 lists the output that can be obtained from BALINT and Table 2 is a typical output chart.

To carry out these calculations it is necessary to input information about the properties of the lift charge, the shell and the mortar. In particular, the size and shape of the lift charge grains are essential data for the code. In all the calculation presented here, we have used for black powder the properties described by Sassé (5) which are similar to those of 2FA black powder.

To reduce the number of variables in determining the effect of various parameters on the output from the code, we have used the standard set of data listed in Table 3. Imperial units have been used is the calculations since there are some problems in the code with metric units.

RESULTS AND DISCUSSION

The effect of various parameters in the model on the time profiles of pressure, speed and lift charge consumption will be described. The standard set of data listed in Table 2 was used as each parameter was varied. In a few cases, data had to be altered in to obtain meaningful results from the output. These cases will be noted in their particular section. Where appropriate, the results of the calculations will be compared with experimental results, but it should be borne in mind that initial adjustment to experimental results was achieved by altering the friction coefficient and leakage area.

Effect of Friction Coefficient, C_f

The effect of C_f is illustrated in Figure 1, from which it can be seen that the speed of the shell increases as C_f increases. Higher values of C_f indicate lower values of "friction" and conversely. Thus, increased peak pressure, exit times and lift charge consumption are observed at low values of C_f.

Effect of Leakage Area (used $C_f=5$)

Figure 2 shows the effect of leakage area on pressure, speed and lift charge consumption. As the leakage area increases, speed decreases and lift charge consumption increases, as expected. However, it is also noted that peak pressure increases and it is difficult to explain this observation. The opposite effect is observed from the ratio $(d/D)^2$ as reported experimentally. A direct comparison with experimental results will be discussed later.

Effect of Chamber Volume (Volume under shell) V_{ch}

The effect of the chamber volume on the pressure and speed profile is shown in Figure 3. Increasing the chamber volume decreases the peak pressure. Both the exit speed and lift charge consumption are essentially independent of the chamber volume, although higher speeds result earlier at lower chamber volumes. Thus, it is possible to obtain the same height for the shell with a larger chamber volume and increase the life of the mortar since lower peak pressures are experienced.

Stationary Shell

These results are linked to the previous study of the effect of chamber volume. Figure 4 shows the peak pressure reached in the mortar as a function of mass of lift charge for three different chamber volumes. The friction coefficient was set to zero, so that there was no movement of the shell in the mortar. The leakage area was also set to zero so that the maximum pressure consistent with the mass of the lift charge and the chamber volume used, resulted.

It is noted that lower peak pressures are achieved with larger chamber volumes, as previously observed and, as the chamber volume increases the peak pressure becomes independent of the mass of the lift charge. Finally, as the mass of the lift charge increases the peak pressure increases and the time to reach this pressure decreases.

Effect of Shot Travel (Mortar Length)

As expected, the speed, time to exit and lift charge consumption increase with mortar length. This is indicated in Figure 5. The peak pressure remains constant. Thus, the code predicts the same effect for the speed and peak pressure as observed in the experiments.

Effect of Mass of Lift Charge

Figure 6 depicts the effect of the mass of the lift charge on the calculated parameters. As the mass increases the peak pressure, speed and lift charge consumption increase and the peak to exit time decreases. Again, these results agree with experimental results.

Effect of the Mass of the Shell

From Figure 7, it can be seen that increasing the mass of the shell increases the peak pressure and lift charge consumption but decreases the speed, as expected. No minima in peak pressure and speed were detected, as reported from the experiments.

Effect of "Fit"

The results shown in Figure 8 represent an attempt to directly compare the predictions from the model with experimental results. The $(d/D)^2$ values quoted by Contestabile et al (1) were used to estimate the leakage areas given in Figure 8. As $(d/D)^2$ increases, the leakage areas decrease. In these calculations, C_f was set to 5 since higher values caused the code to generate floating point errors. The results indicate that the small differences in leakage areas resulted in very little difference in the pressure and speed profiles. This is definitely a limitation of the present code.

BLACK POWDER GRAIN PARAMETERS

Effect of the Diameter of the Spherical Grains

Figure 9 shows that the diameter of the grains of black powder has a dramatic effect on the peak pressure and, correspondingly, on the speed of the shell both in the mortar and at exit from the mortar. The latter affects the height that the shell attains. Smaller grains yield higher peak pressures, speeds and increased consumption of black powder. This is believed to be a result of the increased burning rate with grains having larger surface area to volume ratios.

Effect of the Shape of the Grains

The effect of the shape of the black powder grains on pressure and speed profiles is indicated in Figure 10. These calculations were done for cord, cylindrical and strip grains having the same volume as the spherical grains (diameter 0.12 in.) used in the standard set of data in Table 3. The peak pressures and speeds increase in the order spherical to cylinder to strip to cord, the order of increasing surface area and expected increase in burning rate. There is flexibility in adjusting the size parameters, particularly for the strip and cord and yet retaining the same volume. In general, the peak pressure and speeds are reduced as the strip approaches a cube and the cord approaches a cylinder.

Effect of Mixture of Sizes of Grains

Figure 11 compares the results of the standard set of data with a mixture of spherical grains containing equal mass of grains of diameter 0.08, 0.10, 0.12, 0.14 and 0.16 in., respectively (C_f = 5.0 and leakage area nil). This graph shows little difference between the results for the two sets of data, although peak pressures and speeds are slightly larger for the single grain case. This implies that the slower burning rate of the larger grains has a large influence on the result. It is probably more realistic to expect an unequal mass distribution of grain sizes (2)(5) and these results are merely intended to illustrate the limits to which the code can be extended.

Effect of Mixture of Grain Shapes

Calculations have been done for a mixture of spherical and cubic (strip) grains of equal mass and size (0.12 in.). These results are shown in Figure 12, along with the results for spherical grains under the same conditions (C_f = 5.0 and leakage area nil). Clearly, pressures and speeds for the mixture of grains are lower than those for the spherical grains. This result is believed to be caused by the slower burning rate of the cubic grains.

Effect of the Lift Charge Consumption (Mortar Length)

Figure 13 shows the time profile for black powder in the form of grains which are strips. This information illustrates the trend in pressure and speed for the case where all the lift charge is consumed prior to the shell reaching the end of the mortar. Inflection points in both the pressure and speed profiles are observed particularly for the "thinnest" grains. Additionally, Figure 13 demonstrates the effect of the size parameters on the magnitude of the peak pressure and exit speed. As the grains become more cubic, the peak pressure, exit speed and lift charge consumption decrease.

CONCLUSIONS

The ballistics model provides useful information about the performance of fireworks in a mortar. For the most part, there are good correlations with the trends observed in experiments. Additionally, the code provides information about effects for which limited experimental results are available. Despite a few shortcomings and obvious errors needing correction, it appears that additional calculations using BALINT are warranted.

ACKNOWLEDGMENT

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Table 1 - Output from BALINT

1. Time profiles of pressure, speed distance and amount of lift charge consumed
2. The above information for a mixture of up to 5 lift charges differing in size and/or shape eg. spherical, cylindrical, cord, strip (cube)
3. A summary including the time to peak pressure and the time to exit from the mortar, the exit speed and the value of the peak pressure
4. A summary of the energy distribution including that released by the lift charge and that consumed by various means such as internal gas, kinetic energy of the shell, heat loss, kinetic energy of the gas, friction, leakage, etc.

Table 2 - Output information from BALINT

```
 TIME          PRESSURE (PSI)          VELOCITY  TRAVEL      BURNT
              ---------------------                       PROPELLANT
 (MS)     CHAMBER   BREECH   BASE       (FT/S)    (IN)      (Bpwd)
-------------------------------------------------------------------
    .2       34       34       34           4     0.00       0.01
    .4       63       63       63          17     0.02       0.02
    .6       90       90       90          37     0.09       0.03
    .8      109      109      109          64     0.21       0.04
   1.0      117      117      117          94     0.40       0.04
   1.2      116      116      116         125     0.66       0.05
   1.4      108      109      108         155     1.00       0.06
   1.6       98       98       98         183     1.40       0.07
   1.8       87       87       87         207     1.87       0.08
   2.0       77       78       77         229     2.40       0.09
   2.2       69       69       68         248     2.97       0.10
   2.4       62       62       61         266     3.59       0.10
   2.6       56       56       55         281     4.24       0.11
   2.8       51       51       51         295     4.93       0.12
   3.0       47       47       47         308     5.66       0.13
   3.2       44       44       43         320     6.41       0.14
   3.4       41       41       40         331     7.20       0.14
   3.6       38       39       38         342     8.00       0.15
   3.8       36       36       36         351     8.84       0.16
   4.0       34       35       34         361     9.69       0.16
   4.2       33       33       32         370    10.57       0.17
   4.4       31       32       31         378    11.46       0.18
   4.6       30       30       30         386    12.38       0.18
   4.8       29       29       28         394    13.32       0.19
   5.0       28       28       27         401    14.27       0.20
   5.2       27       27       26         408    15.24       0.20
   5.4       26       26       26         415    16.23       0.21
   5.6       25       26       25         422    17.23       0.22
   5.8       25       25       24         428    18.25       0.22
   6.0       24       24       23         435    19.29       0.23
   6.2       23       24       23         441    20.34       0.24
   6.4       23       23       22         447    21.41       0.24

 MUZZLE VELOCITY          :    450. FT/S
 BASE PRESSURE MAXIMUM    :    118. PSI
 CHAMBER PRESSURE MAXIMUM:     118. PSI
 BREECH PRESSURE MAXIMUM :     118. PSI
 TIME TO MAXIMUM PRESSURE:     1.06 MS
 TIME TO EXIT             :    6.51 MS
```

Table 3 - Cylindrical Shell

Mass of lift charge, m = 3.5 oz$^+$

Mass of shell, M = 3.0 lb

Black powder - spherical grains - diameter 0.12 in$^+$

Shot Start Pressure 20 p.s.i.$^+$
(chamber pressure required to initiate movement of the shell in the mortar)

Chamber Volume, Vch = 70 in^3
(volume under shell)

Shot Travel 23 in
(assumed to be equal to mortar length, ie. neglect effect of shell size)

*Leakage Area 20 in^2
} assumed constant
*Friction Coefficient 15

* These parameters have been adjusted to give reasonable agreement with experimental values of peak pressure and exit speed (1). Leakage area option is not as yet available in code when using a mixture of grains of black powder of different sizes and/or shape.

+ 1 in = 2.54 cm
1 p.s.i. = 6.89 kPa
1 ft s^{-1} = 30.5 cm s^{-1}
1 oz = 28.3 g

Figure 1

Effect of Friction Coefficient

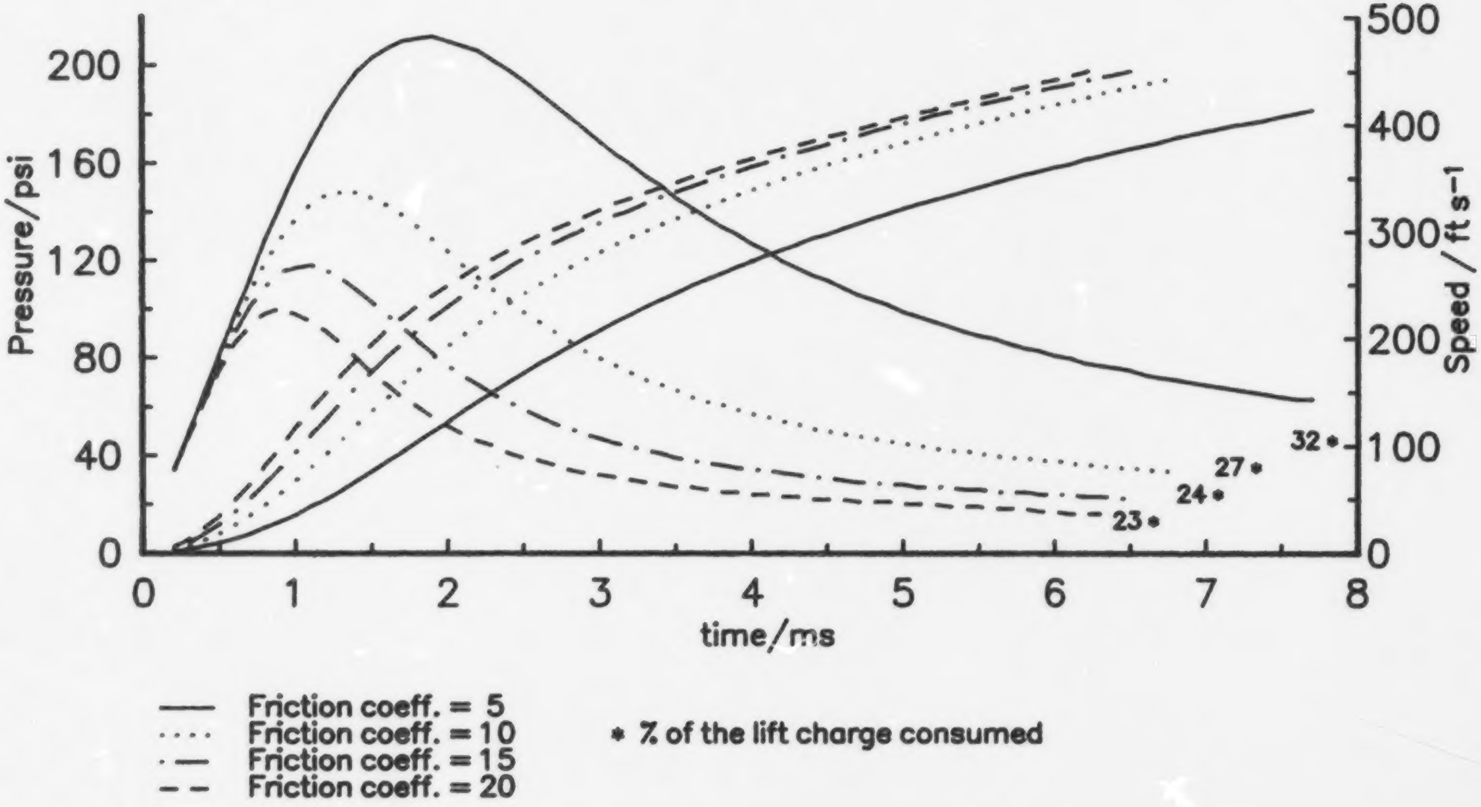


Figure 2

Effect of Leakage Area

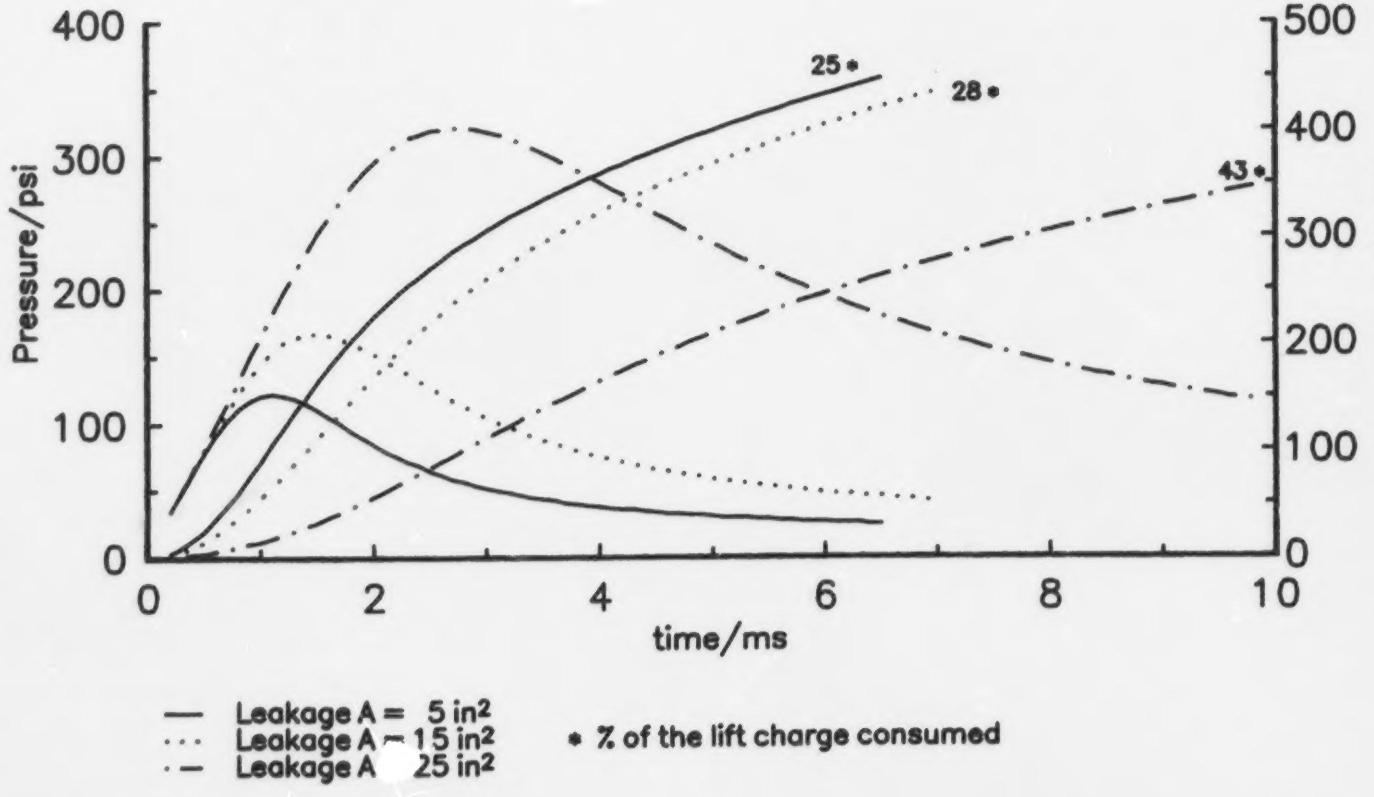


Figure 3

Effect of Chamber Volume

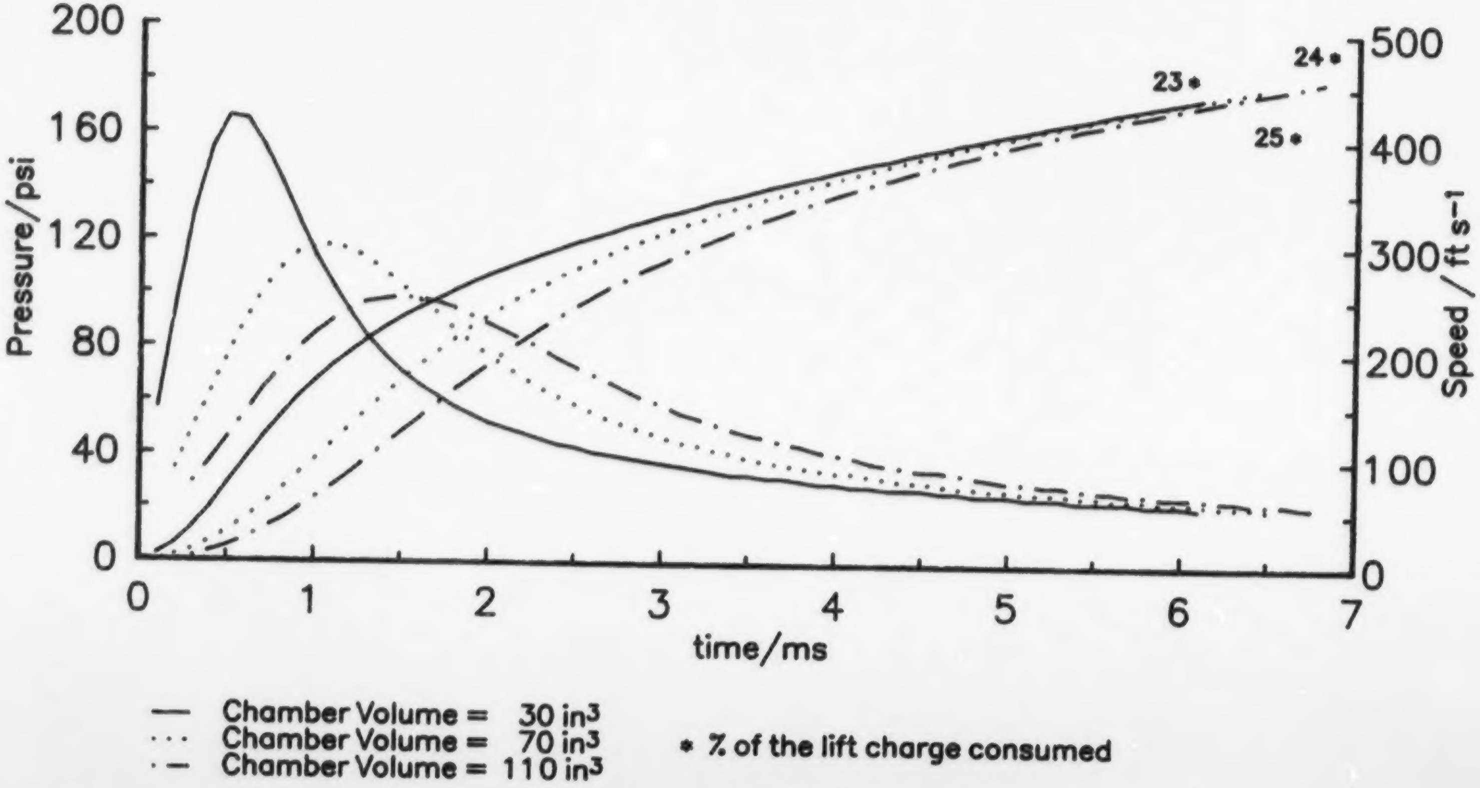


Figure 4

Stationary Fireworks Shell

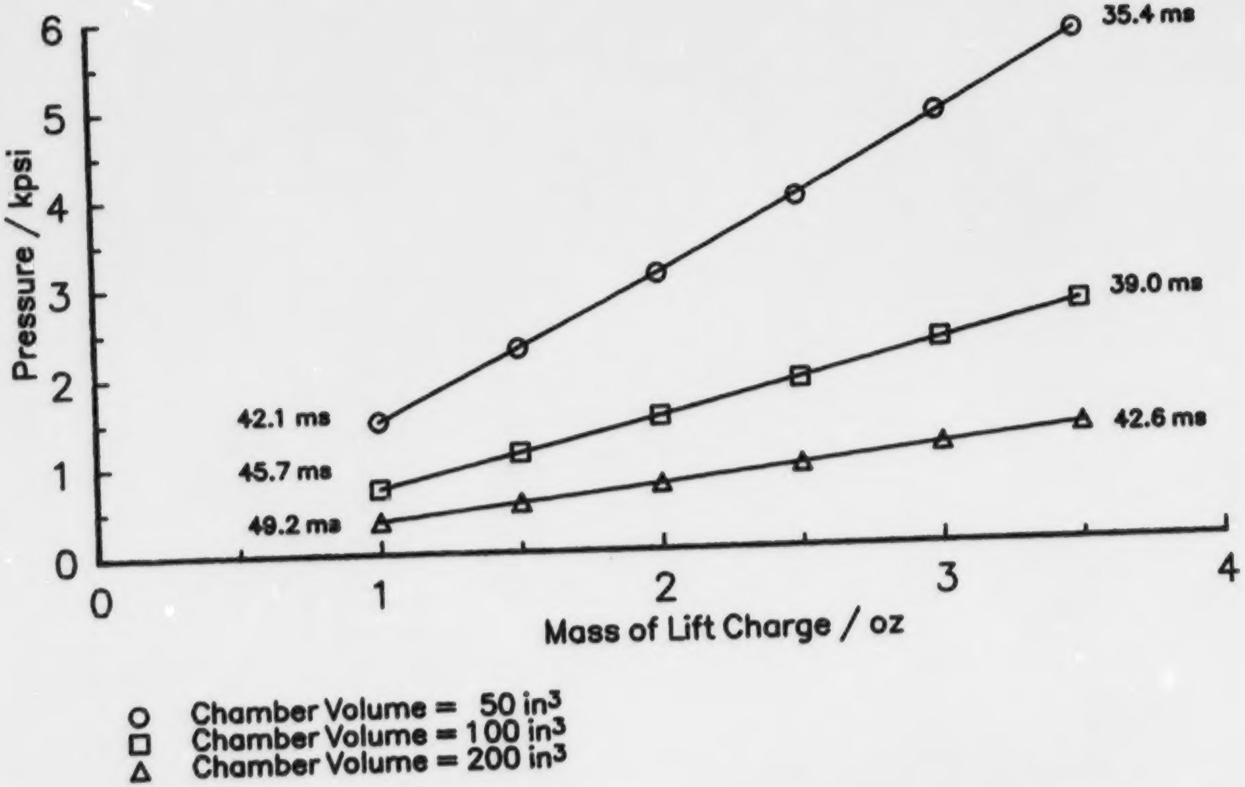


Figure 5

Effect of Mortar Length

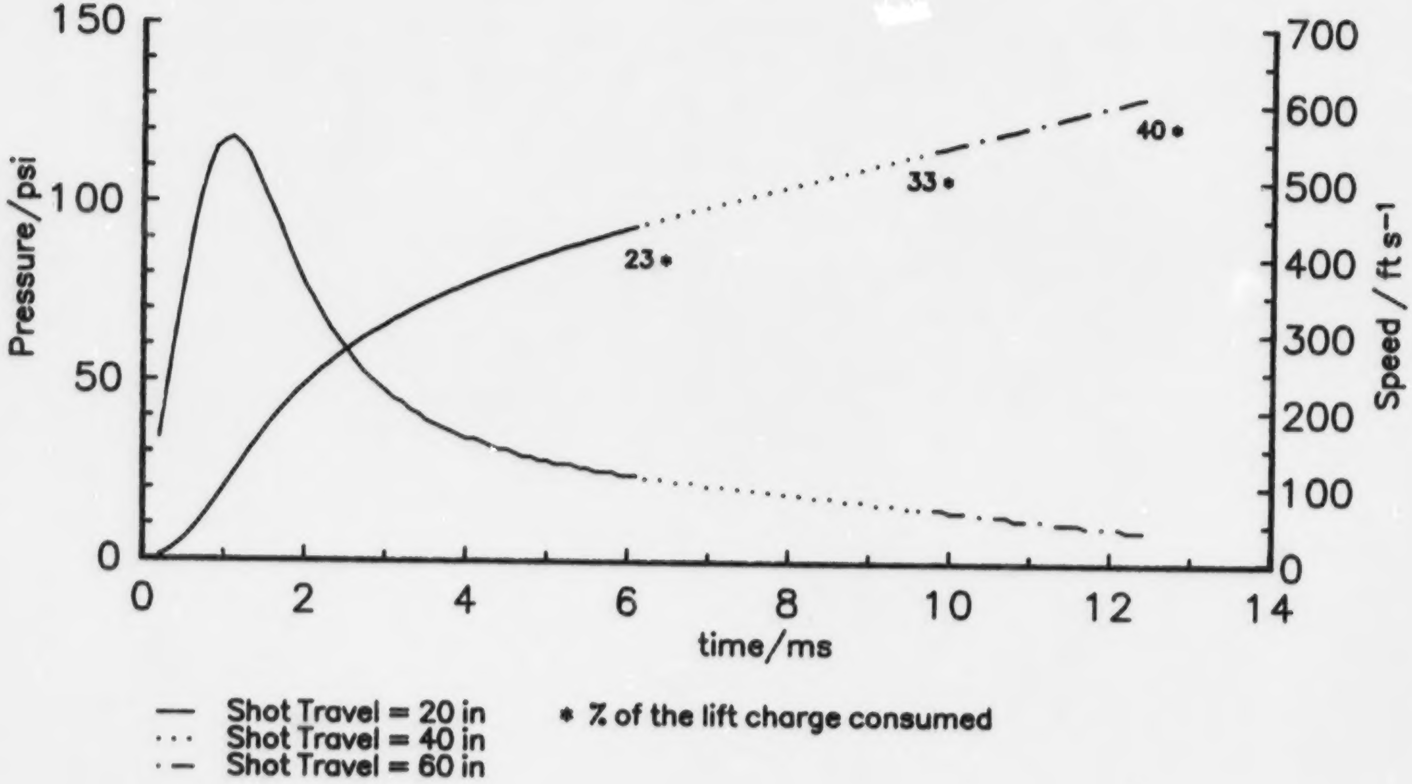


Figure 6

Effect of Mass of Lift Charge

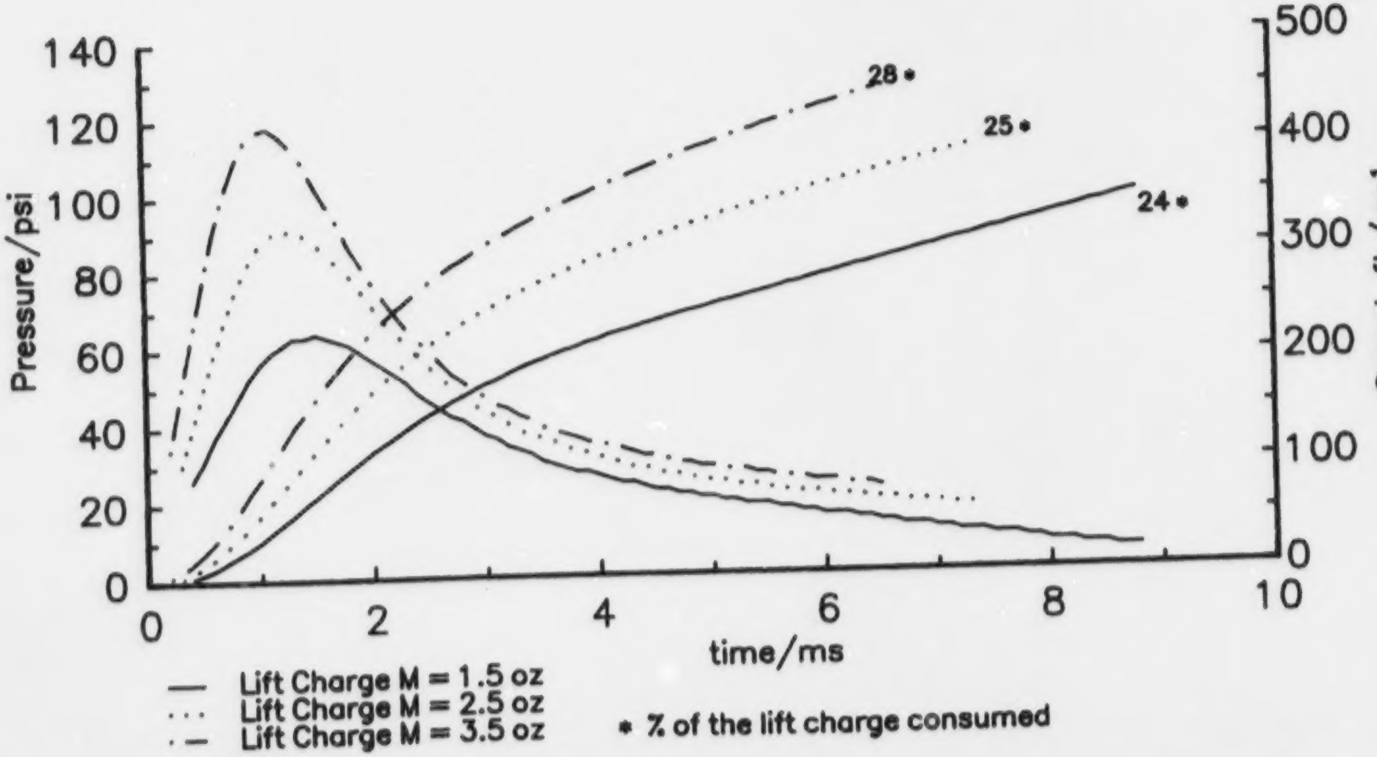


Figure 7

Effect of Mass of Shell

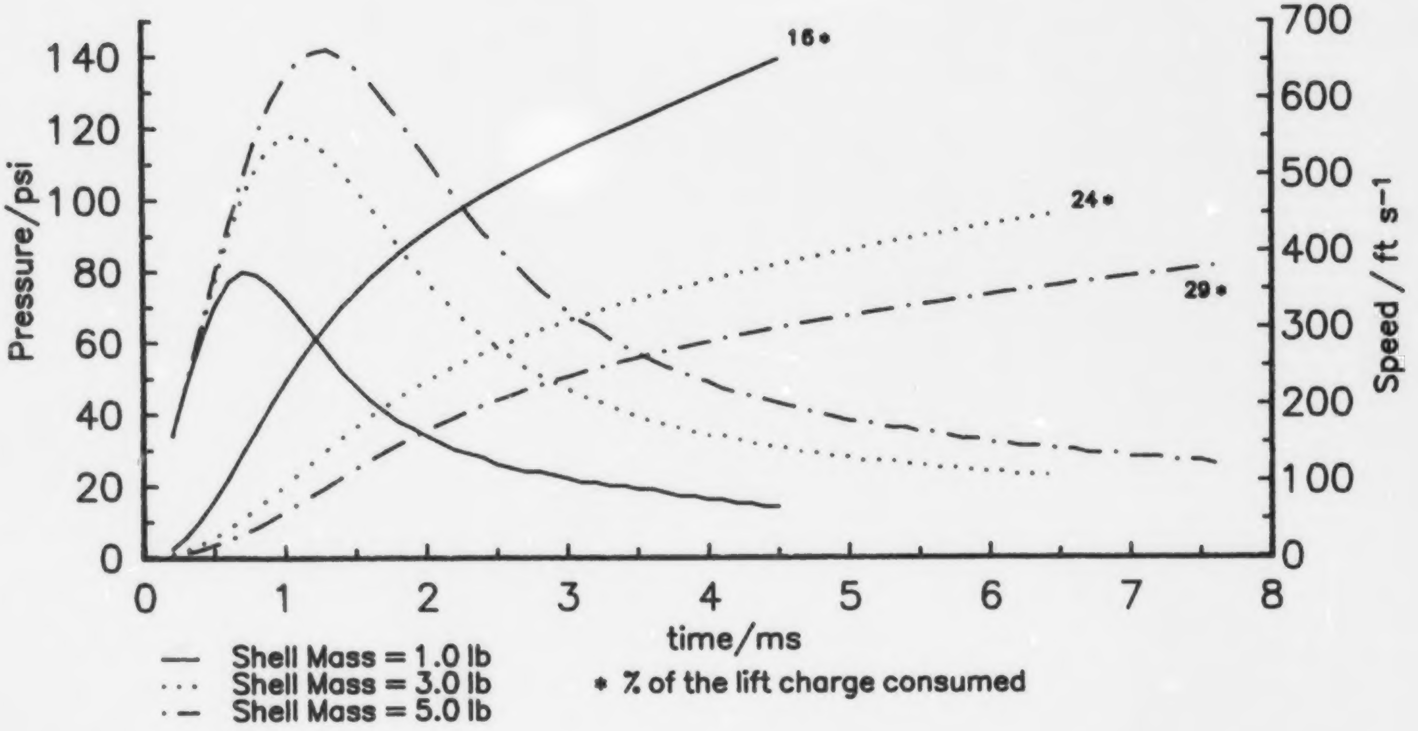


Figure 8

Effect of "Fit"

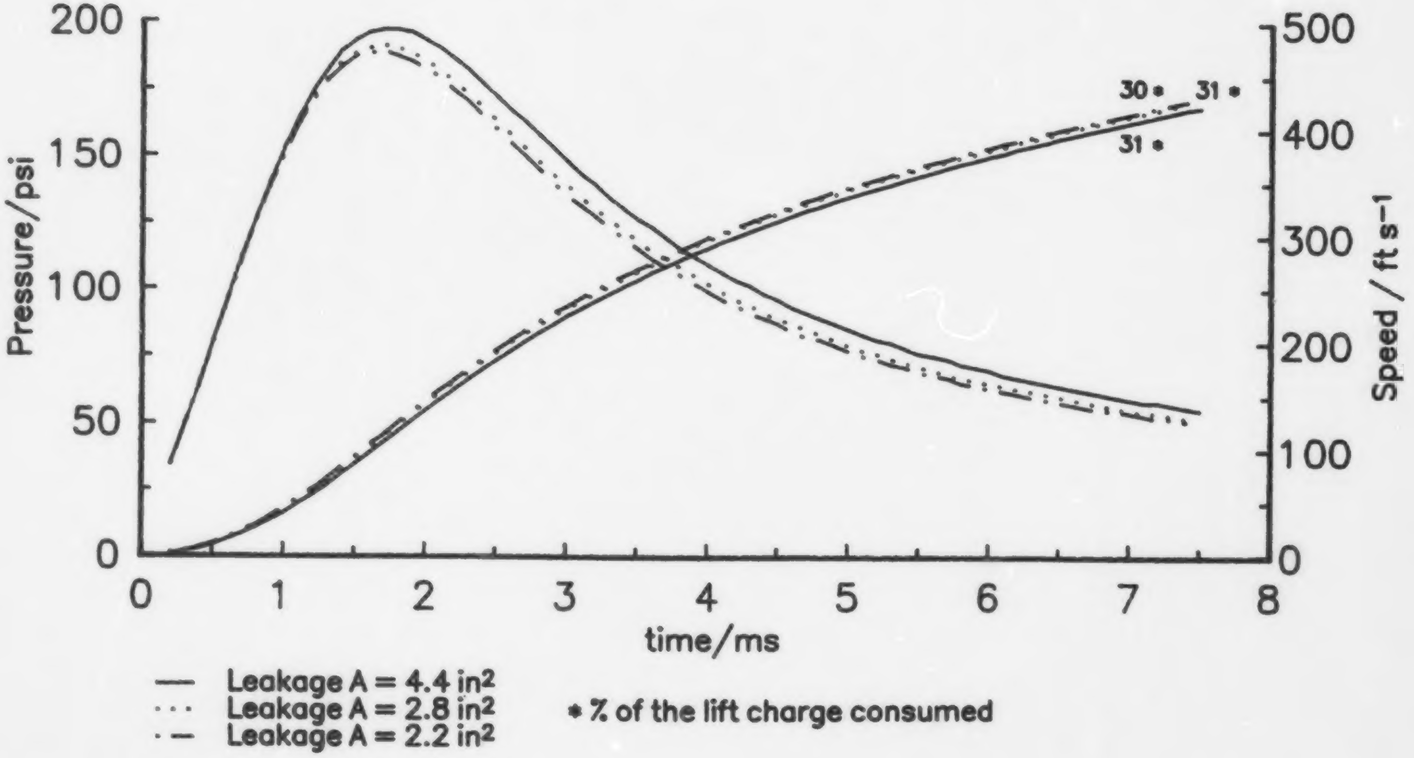


Figure 9

Effect of Size of Lift Charge Grains

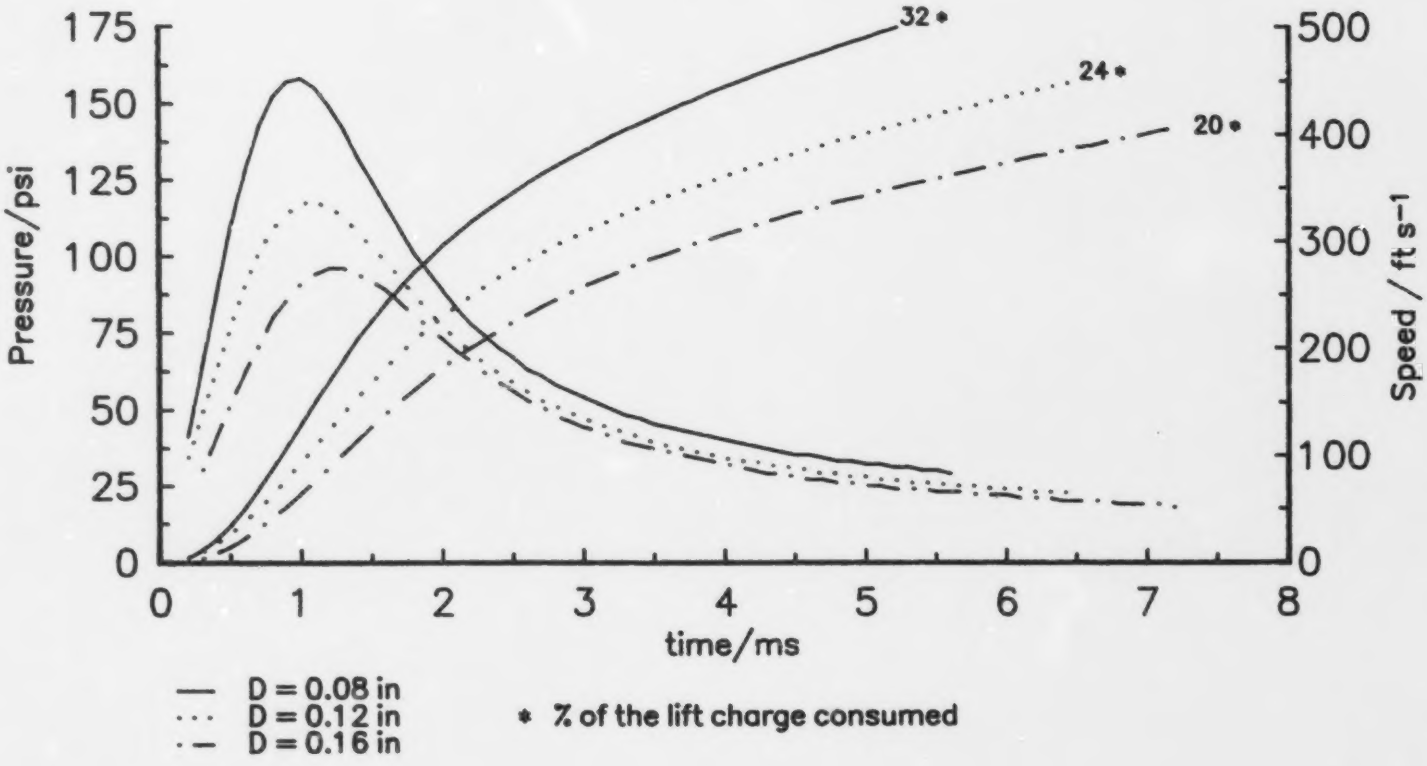


Figure 10

Effect of Shape of Lift Charge Grains

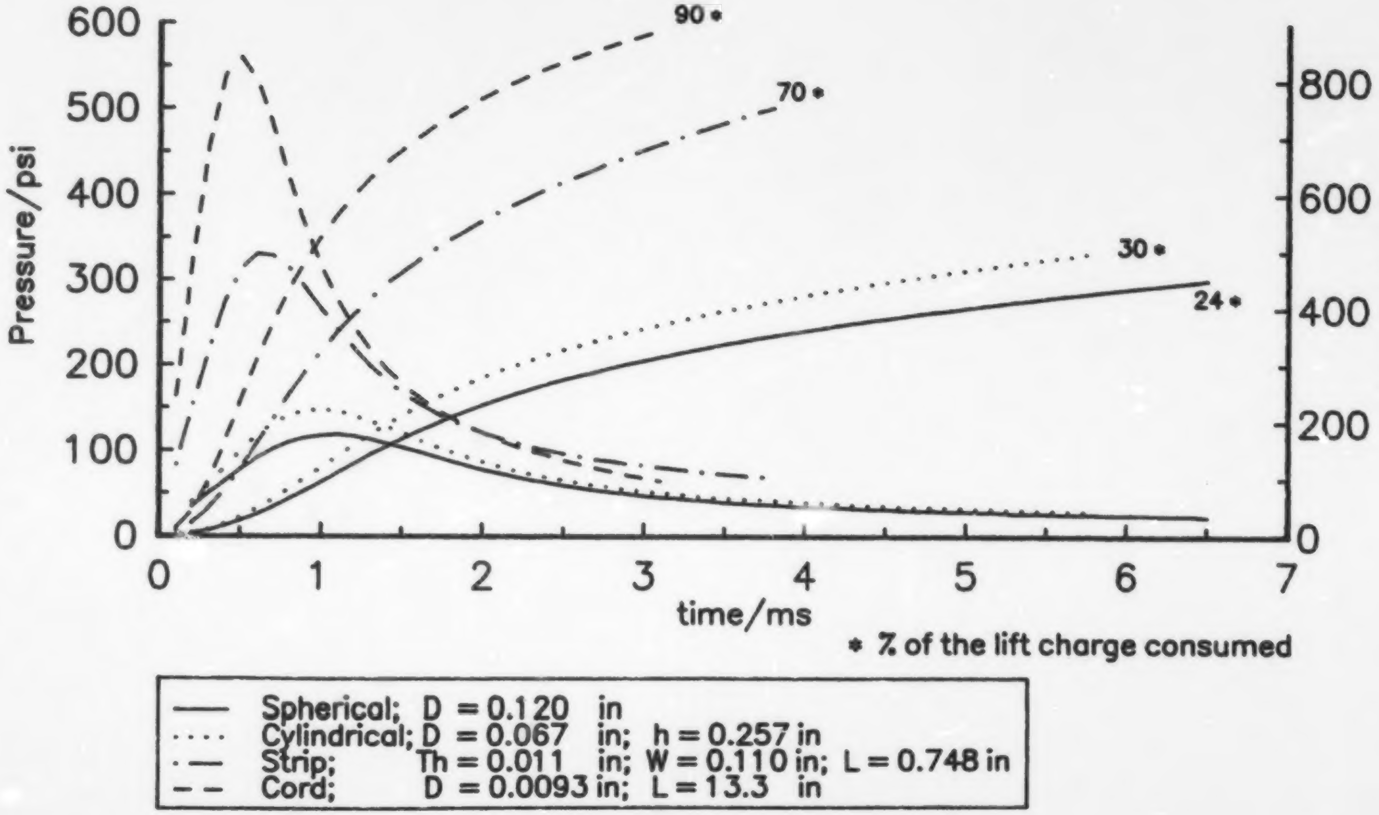


Figure 11

Effect of Mixtures of Sizes of Lift Charge Grains

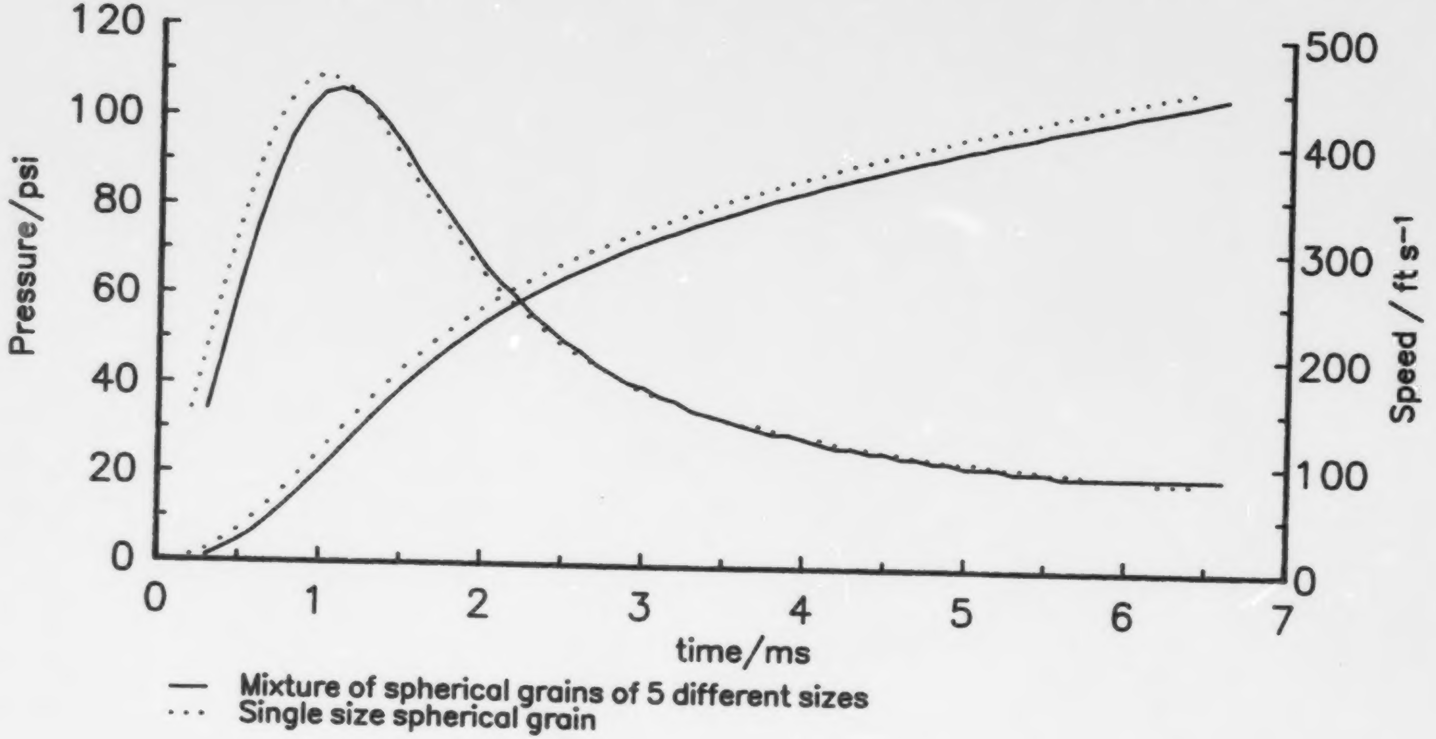


Figure 12

Effect of Mixtures of Lift Charge Grain Shapes

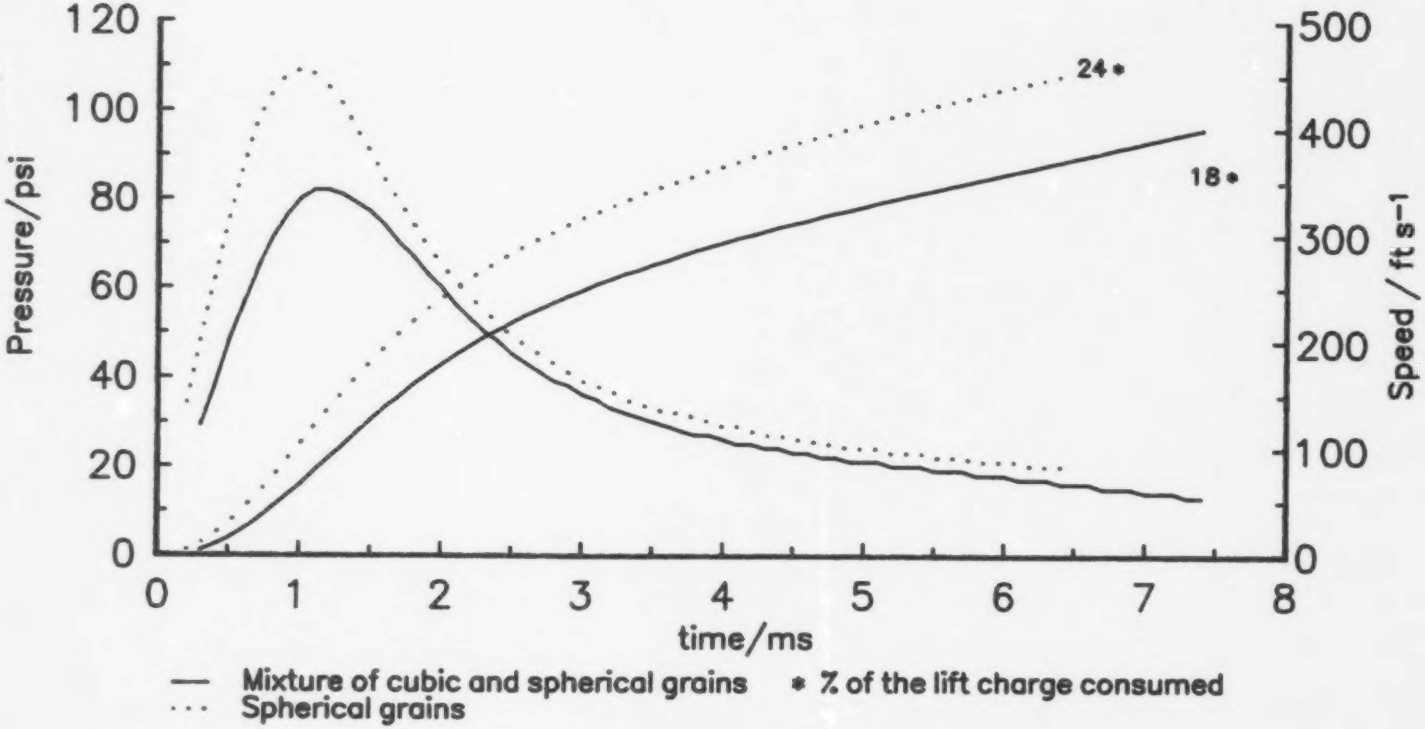
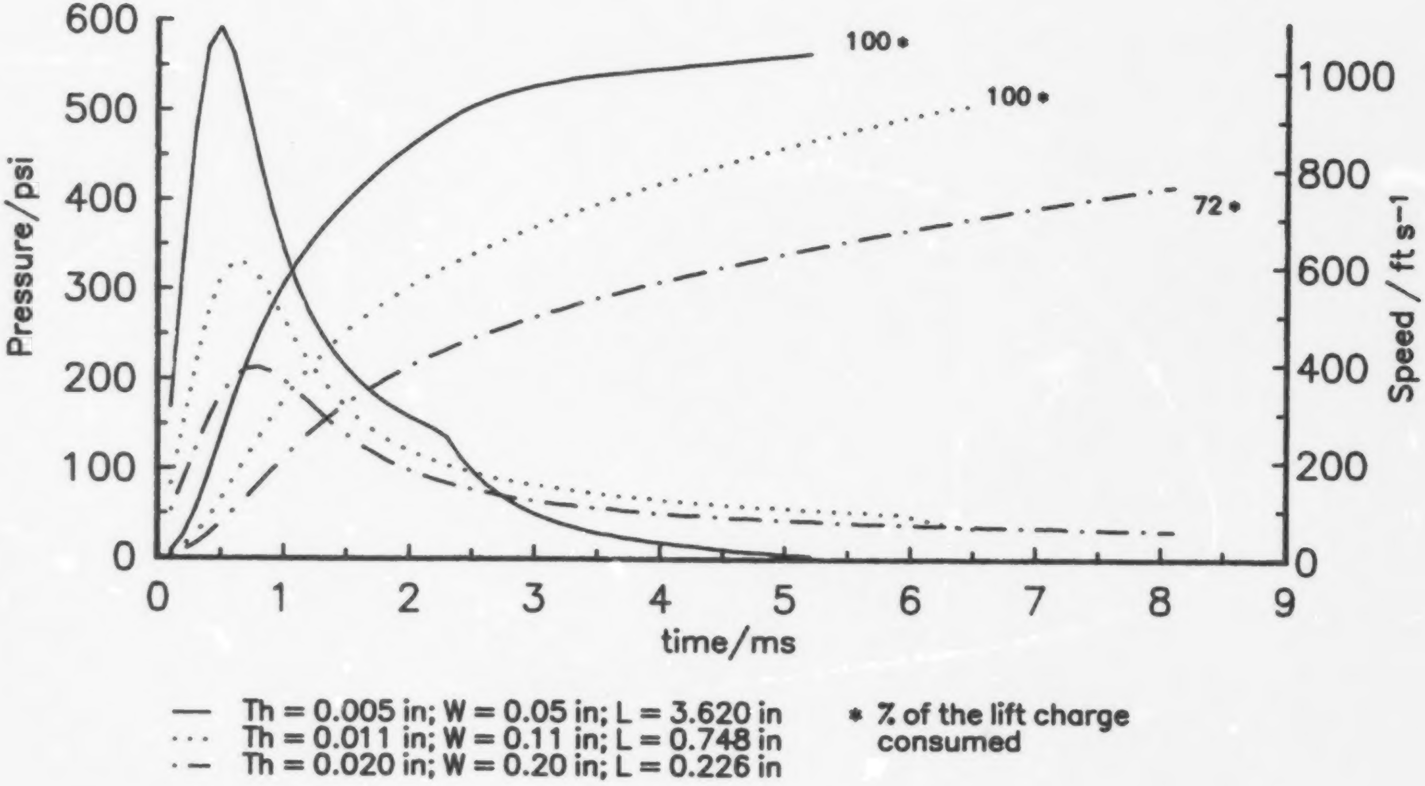


Figure 13

Effect of Strip Grains in 50 inch Mortar



INSURANCE FOR FIREWORKS COMPANIES

(Pyrotechnic Liability Exposures; Risk Management and Insurance Alternatives)

Presented on 15 May 1992
at the
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INTRODUCTION

The Pyrotechnic Industry is varied, spreading from the smallest firecracker to the largest specialized military items of destructive force. Our expertise lies with the so-called "Class B" display fireworks, their manufacture, storage, transportation and firing. We hope our remarks will be of interest to all engaged in this fascinating business

The nature of the industry deals with materials considered hazardous which in many jurisdictions puts the fireworks company in the indefensible position of absolute liability in the event that anything goes wrong. We will be happy to respond to questions regarding property insurance, vehicle insurance, time element insurance and Workers' Compensation, but would like to concentrate this talk on third-party liability exposures and their mitigation through elimination, assumption or transfer. Inventory losses are quantifiable, as are time-element exposures, although both (in the case of display companies) are highly seasonal.

Third-party liability claims, on the other hand, for bodily injury and/or property damage (allegedly caused by malfunction or mishandling of pyrotechnic products) are subject to the vagaries of juries, attorneys, expert witnesses and the image presented by the injured party.

I. RISK MANAGEMENT CONSIDERATIONS

The basic elements of Risk Management (note that these words are generally capitalized) are firstly a thorough evaluation of your current operations and procedures, including exposures, safety programs, contracts, insurance and personnel. Secondly, the most basic safety tenant of all is top Management Commitment so that safety and risk management administrators are known to have authority supported by the Board of Directors or owners of the company.

Risks which could erode the financial stability of the company should be identified as to "dynamic" or "static" risks. "Dynamic" risks are business risks relating to production of a product or service, its pricing and sale, and the eventual profit if all goes well. The dynamic exposures of recession, style change, business competition and financial credit are not a subject of this discussion. "Static" risks, however, can be listed and evaluated, and the process of Risk Management can begin.

Static risks are known physical exposures inherent in the product or its process where historic statistics allow an evaluation. Once a static risk has been identified and its worst-case effect has been quantified, the following five steps can be considered:

1) The first choice would be total elimination of the risk by dropping the product. In many cases a study will expose a product or process which has enormous exposure but which derives very little net profit. Can that exposure be ELIMINATED without loss to other parts of the business?

2) A review of historical data in regard to claims may detect a pattern, where loss control could take over to reduce this exposure to an assumable size (an example would be moving the parking area to reduce the number of cars which could be damaged by an errant shell or fallout). MITIGATION THROUGH LOSS CONTROL, including adherence to NFPA standards and a good instructional safety program, would partially manage this risk.

3) Top Management should evaluate their financial capabilities to assume risks and set a figure which could be incurred without jeopardizing the financial stability of the company. This ASSUMPTION OF RISK THROUGH SELF INSURANCE should have limits which are monitored to key in alternative forms of risk management when exceeded.

4) TRANSFER OF RISK THROUGH CONTRACT is a very helpful method of risk control which costs nothing. An example would be to put heavy responsibility for security during a display and subsequent pick-up on the show sponsors, relieving the display company of most claims other than a firing error. Some sponsors, where the display is a minor part of the whole event, will agree to name the fireworks company on their insurance.

5) TRANSFER OF RISK THROUGH INSURANCE. This is the last resort after (1) through (4) above. When you find a risk which (a) cannot be eliminated; (b) cannot be brought down to controllable size; (c) is too big to self-assume and (d) cannot be readily transferred through contract, the remaining option is to pay a fixed price to a professional risk taker (an Insurance Company) to take the risk off your hands. In many cases a strong fireworks company can combine (3) and (5) by assuming a large, affordable deductible and only buying insurance excess of the amount it determines is reasonable to self-assume.

II. INSURANCE APPROACH TO LIABILITY EXPOSURES

There are many aspects to liability exposures and the nature of the product adds some interesting dimensions. Let us start with:

1) Premises liability reflects the importation, manufacture, labelling, packaging and storage of hazardous materials, either in the form of component parts or finished devices. The NFPA 1124 guidelines are very useful in this instance, and most Fireworks plants are now composed of a number of small separated structures with temperature, humidity and static electricity controls. Underwriters understand this, and in the case of our companies, we are able to include premises liability at no additional charge if products and display covers are insured and premium paid on receipts. Exposures here are injury to a member of the public or damage to property of others in the case of a plant explosion or fire.

2) Products liability is often misunderstood. It only relates to alleged malfunction of a product after its sale to an outside party and his ignition and use of the product which results in an unexpected accident injuring people or causing damage to property of others. Products liability is not applicable where the insured company fires its own products. Thus, two elements must be proved:

   a) that a product malfunction (not shooter error) has occurred and it was the proximate cause of bodily injury and/or property damage; and

   b) that the product had been used in accordance with all standards, instructions, label designations, etc., and that the product was, at the time of firing, in the same condition as it was on receipt from the subject company and not damaged by mishandling or improper storage.

   In most cases these days, true product liability based on malfunction will be tracked back to the original manufacturer, be it in China, Japan, Brazil or Taiwan, so importers should inquire and receive assurances that their suppliers have insurance which will respond if called upon. Most policies carry at least a $5,000 deductible, so this is exposed plus an adverse rating if suppliers cannot be called upon to pay. In the U.S. you should anticipate paying around 9% of gross sales (excluding Display Revenues) for $1,000,000 limits on Products Liability.

3) Display Liability. This is the point of the largest exposure and the smallest area wherein to hide. Since most displays involve a large crowd and much property nearby (including parked cars), it is essential that all safety programs be fresh in the crew's mind and that as much liability as possible has been transferred to the sponsor(s), including at least the grounds security, before, during and after the show (including pick-up). A recent court case in the State of Washington declared that a display operator had "absolute" liability due to the dangerous nature of the product without the plaintiff's having to prove negligence. This is very disheartening to the trade and to insurers, many of the latter of which have dropped out of competition in this field. Based on current rates, a company should plan on paying 9 - 12% of display receipts for $1,000,000 with discounts being given for fixed-site, repeat shows such as amusement parks. Our blanket policy covers all diplays even if a certificate is not required by the sponsor, and there are no territorial limits.

III. SOME TYPES OF CLAIMS ENCOUNTERED, AND POSSIBLE AVOIDANCE OF SAME

Not all of the following were claims we incurred, but are typical of the wide spread of claims and the need for an executive commitment to a Risk Management program.

1) Premises claims. These seem to be the least prevalent and mainly involve damage to owned property which would be covered under Property Insurance since liability does not cover property of the insured or property of others in his custody or control; it also may involve injury to employees who have recourse to Workers' Compensation benefits and are generally excluded under a liability form. This leaves the possibility of a neighborhood of broken windows, but most manufacturing plants are situated away from major urban areas and away from adjoining structures. A major recent claim involved a suicide, taking the plant with him. You cannot anticipate this type of risk.

2) Products liability claims. We have a few of these, some serious. One involves a show sold to a city where a large foreign shell exploded shortly after leaving the muzzle, knocking down a worker carrying another shell, which ignited and seriously injured five workers - the first shell proved to be one of many with suspected defects and the foreign supplier's insurance will probably pay most of this. A second claim involved a sold show and an alleged malfunction of a salute, driving piece of the cardboard mortar into the worker's hand;this one will be contested in that the mortar was an old one and may have been improperly stored by the buyer, the salute may have been damaged by rough handling, losing it lift charge, etc. A third is a complicated case involving five suppliers of smoke compound, flash, quick match, electric match, etc., plus the creator of the malfunctioning special effects device - all may combine to buy off this in varying amounts, since the combined attorneys' fees for fighting it could exceed the proposed settlement.

3) Display liability. These are the unhappiest in scope and in the end result that both the plaintiff and defendant feel that they came up short. There are clear-cut cases of an errant shell landing in a crowd (rare, but widely publicized cases), and many for new car paint jobs (many of these are clear fraud), but some of the ugly ones involve kids supposedly picking up items after a show and hurting themselves (it seems to be a tough battle proving that the devices came from illegal sources, the parking lot, devices left by the crowd, etc.). We have one case of a man suing our display company for injuries incurred in a fight before the fireworks show due to improper security. We even have a record of a settlement for a boy struck by lightning while watching a show - supposedly he would have not have sneaked out of the house and stood under the tree in the rain unless there had been a show! We have cases we are fighting because of supposed sabotage, home-made device insertion, contributory negligence, fraud, etc. However, the deep pocket and visibility of the display company makes it vulnerable to such suits.

For some good background information on fireworks insurance, I refer you to BEST'S UNDERWRITING GUIDE (7/90) under "FIREWORKS MANUFACTURING AND EXHIBITING" which I helped formulate.

The following page is from my associate in London regarding the insurance market at present.

William Kent, III

PART TWO

I. INSURANCE MARKET OVERVIEW (LLOYD'S UNDERWRITERS)

As I am sure you are all aware, Lloyd's of London is pre-eminent as a center for innovation in Insurance; it is world's leading insurance market and a class leader which is both highly flexible and competitive.
Lloyd's of London is synonymous with excellence, quality and security.
No valid claim has gone unpaid. Lloyd's is a society of individuals engaged as sole traders in the transaction of Insurance business, trading on the basis of unlimited liability. Each member is required to show a minimum level of personal wealth of £250,000, but members are individually liable to the full extent of their wealth. Lloyd's is not a Insurance Company.
Lloyd's is made up of individuals and collectively in 1991 had a market capacity of in excess of £ 10 Billion of premiums. Lloyd's accounts for approx. 1.75% of the worlds non-life premiums; approx. 70% of its business comes from overseas 40% of which emanates from the U.S., 10% from Europe and 15+% from other territories.
There were 26,568 members participating in 1991 of which 5,044 were overseas members of Lloyd's from more that 80 countries. There are 1,647 participating U.S./Canadian members providing Lloyd's with approx 10% of the overall capacity of Lloyd's.
In 1992 there are 275 syndicates operating in the Lloyd's Market, and in 1992 there are over 200 Lloyd's Brokers.
The security behind Lloyd's policies is uniquely strong; strict procedures ensure funds are always available to meet valid claims which are paid as soon as they have been agreed. The aggregate available resources of the society of Lloyd's exceeds U.S. $40,000,000,000.
As a matter of interest it is estimated that the Lloyd's market provides employment for more than 8,000 people, either directly or indirectly.

II. CANADA AND THE U.S.A.

The U.S.A. and Canada are a very substantial provider of business to Lloyd's.
70% of all business is written in U. S. Dollars
55% of this (40% approx. overall) is U.S. domestic business; the remainder is from U. S. insurance transactions which are expressed in U.S. Dollars
Lloyd's has actively underwritten American business for over 100 years and early clients still place their business with Lloyd's. For instance Sears Roebuck has continually purchased it's Liability Insurance from Lloyd's and the London Corp Market since 1940. Lloyd's Underwriters were licensed to accept business in the Province of Quebec in 1932 and subsequently in all Canadian Provinces
All U. S. Dollar premiums - regardless of origin - are held through Lloyd's American Trust and Lloyd's Canadian Trust Funds and both these funds amount to more than $8,000 million. The Canadian Fund at approx. $800,000,000 exceeds the amount required by the Minister of Finance's Federal Registry by more than $125,000.000. Lloyd's is one of the largest investors in U.S. Government "paper"; the second largest contributors to Internal Revenue Service of all U. S property and casualty insurers.

Brian Wilkin

TITLE

TRANSPORT CLASSIFICATION OF COMMON FIREWORKS

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ABSTRACT

As the official authority in The Netherlands for the classification of explosives for rail and road transport, TNO has performed the UN classification of about 500 common small fireworks articles.
The classification was performed in two steps. First the 500 firework articles were divided into a small number of characteristic families. This reduced the number of tests and therefore the costs of classification. For performing the second step, the actual testing, articles with the heaviest mass of explosive and, in our opinion, the most dangerous pyrotechnic composition of each family were chosen.

The decisive UN tests to be performed were selected for each family depending on the kind of pyrotechnic composition and the construction of the firework articles.

The results of the UN tests led to the following classification: common small firework articles are classified in hazard division 1.4S, with the exception of the family "rockets". The rockets gave fiery projections which were thrown more than 15 m from the edge of the stack and indented the aluminium witness screens. Therefore they were candidate for hazard division 1.3G.
Consequently, transporting in the same container, 1.3G and 1.4S will give 1.3G for the total cargo. Tests were then performed to contain the rockets inside the UN-package after ignition, the criterion for 1.4S. Hexagonal netting inside the UN package proved to be effective.

INTRODUCTION

At the request of the Dutch Federation of Firework Traders, financially supported by the Ministry of Economic Affairs, about 500 commercially obtainable common small firework articles were classified for transport (1). The procedure was as follows.
First the 500 different firework articles were divided in 10 families, this work is described in Kodde (2). The second part of the work consisted of the performance of the experiments, test series 4 and/or 6 (3). The experiments were performed with the selected firework article of each family. With the results of the experiments, the classification was performed. All the commercially obtainable common small firework articles are classified in hazard division 1.4S. To classify the rockets into division 1.4S an additional wire netting has to be introduced in the packaging.
The desk study, the experiments and the classification are summarized in this paper.

DESK STUDY

The desk study (2) was performed to reduce the 500 firework articles into a small number of families. Doing so, a considerable reduction in the number of tests and the costs of classification were obtained. This method was chosen because, in spite of their very different appearance, many firework articles contain the same explosive components with almost equal effects.

To perform the selection, a complete data sheet of each firework article was needed. At the present, data sheets are available for about 90 % of the commercially obtainable common small firework articles in The Netherlands. The Dutch firework importer Schuurmans B.V. in Leeuwarden discussed the need of these data sheets with the Chinese firework factories and introduced them. An example of a data sheet is given in Appendix 1.

The families consisted of firework articles with similar pyrotechnic mixtures and similar effects. From each family the articles with the highest mass and, in our opinion, the most sensitive pyrotechnic mixture were selected for testing.

Selection procedure

The firework articles were selected in three steps. The first step took place in accordance with the criteria of the Dutch "List of Fireworks"(4). This resulted in ten family types, presented in Table 1.
The second step consisted of the selection of certain firework articles from the ten families. Experiments (classification tests) were performed with these selected articles. The selection criteria were the differences in pyrotechnic mixture

and mass, the construction of the article, the violence of the explosive reaction and the expected explosion effects.

The choice of the selected firework article of each family type is explained below.

Family type 1, Firecrackers

In this family type the pyrotechnic composition used for all firecrackers was black powder. The item with the largest mass was selected.

Family type 2, Fountains, florals etc.

The most dangerous article was that which gives heat radiation and a report while stars are ejected. From this family a second article (a fountain) was selected which gives heat radiation only.

Family type 3, Illumination torch.

This family type is related to family type 2.

Family type 4, Rockets, ruptured by functioning.

The pyrotechnic compositions are comparable with family type 2, except for the propulsion effect. This is an extra parameter for classification in the UN hazard division. Three rocket types were selected, one with a relatively large rocket motor and small pay-load, one with a small rocket motor and a large pay-load and one with a sensitive, whistling pyrotechnic composition.

Family type 5, Rotating, non rising fireworks.

No articles were selected from this family. They are related to family type 2.

Family type 6, Rockets which do not rupture when functioning.

These rocket types are related to family type 4.

Family type 7, Rotating non rising fireworks without rupture.

From this family no articles were selected.

Family type 8, Rotating, rising firework.

None of the articles which were selected belong to this family type.

Family type 9, Sparklers etc.

From this family the sparkler was selected. The sparkler gives the most heat radiation. Other explosion effects were not expected.

Family type 10, Indoor fireworks.

No articles were selected. The UN hazard division of family 2 firework articles are representative or even too conservative for this family.

Two additional firework packages were added for performing the classification test. These were the blister fireworks and a mix of the articles from all the families.

With the third step in the desk study, the UN test series was selected.

The selected firework articles and the recommended test series are summarized in Table 2.

EXPERIMENTS

The UN test series 4 and 6 were carried out in November 1990 and March 1991. The firework articles were tested in the same condition and form in which they will be offered for transport.

A summary of the description of the test series is as follows:

Test series 4 is intended to determine the overall stability of the packaged article in environments which simulate transport conditions other than fire.

Typical transport conditions include, for example, "high" temperatures and being dropped. This test series consists of two types of tests: test 4(a), the thermal stability test, the temperature is measured with a thermocouple in the centre of the package. Test 4(b), the twelve metre drop test, no registrations are made.

Test series 6 is necessary to determine which hazard division corresponds most closely to the behaviour of the packaged article if a transport load is involved in a fire, resulting from internal or external sources, or an explosion from internal sources. There are three types of tests in this series. Test 6(a) is a single package test, test 6(b) is a stack test, both with internal ignition, and test 6(c) is an external fire test.

The method of confinement consists of sand with a minimum thickness of 0.5 m for test series 6(a) and 1 m for test series 6(b).

The explosion effects: blast, heat radiation and fragmentation are registered.

The blast effect is measured with blastpencils (PCB 137A12) located at 4 and 6 metres from the edge of the stack.

The heat radiation is determined by measuring the temperature and surface area of the fireball.

The temperature is measured with a contact-less infra-red thermometer. Video recordings are made to determine the surface area of the fireball. With the Stefan Boltzmann law, the total irradiance intensity is calculated, see Verhagen 1992 [6].

Fragmentation is registered with witness screens of aluminium sheets (2000 x 2000 x 2 mm). The witness screens are placed in each of the three quadrants at a distance of 4 m from the edge of the stack. No witness screen is placed in the downwind quadrant.

Perforation or indentation of the witness screens are two of the criteria to characterize the fragmentation effect.

The firework articles tested were packed in UN-tested cardboard boxes (5). Three types of boxes were UN tested. Depending on the size of the firework articles, one of the boxes was chosen. The boxes are listed in Table 3.

The firework articles, the type of box, the number of firework articles in the box, the total mass of box and articles and the assessed total mass of the explosives (pyrotechnic mixtures) in the box are listed in Table 4.

RESULTS

The results of the performance of the UN test series are described in Kodde (3). A summary of the observations and the measured results are given below.
With test series 4(a), no thermal instability of the tested firework articles occurred. Test series 4(b) was carried out without the observation of burning or explosive reaction.
With test 6(a), no mass explosions of the total content of tested packages occurred. The steel witness plate showed no damage in any test.
Test 6(b) was carried out with a stack of three boxes. In one box, the three items in the centre were ignited. On the top and against one of the sides of this box, the other two boxes were placed. After the ignition, a small number of firework articles reacted. The other two boxes showed only burning damage on the outside of the box.
In test series 6(c), the blast and irradiance of the firework articles were no more significant than those of the fire itself. The firework articles functioned in the fire and some were found within a radius of 5 metres around the fire.

The rockets needed special attention, 90 % of them reacted in the fire. The lattice of wooden laths behaved as a shelter for propulsion, therefore most of the rockets could not leave the fire. Some rockets, about ten, left the fire and impacted on the aluminium witness screen without penetration. About ten rockets indented the screen and about three were found at a distance of about 50 m from the fire. Subsequently, special attention was paid to contain the rockets inside the UN-tested cardboard boxes, so that hazard division 1.4G, or even 1.4S, would be one of the classification possibilities.
Preliminary tests with modified UN boxes to contain the rockets inside the box, showed good results. These boxes were modified with wire netting or glass wool.
Both modifications contained all the rockets inside the UN box. After performing the fire test the sides of the UN box were still intact, although the rockets had functioned inside the box. A photograph of the UN box with an inner packaging of wire netting, after performing an external fire test, is shown in Figure 1.

The explosions effects which occured in test series 6(c) were irradiance and indentation. The results are listed in Table 5.
The irradiance value of 1600 W/m^2 is the value which will also be measured with the stack of wood only (6). The flame was less than 3 m in all the test series 6(c).

CLASSIFICATION

According to the test results, the commercially obtainable firework articles are classified as 1.4S when packaged in the UN-tested packagings, see Table 3. The firework types with the selected and tested firework articles are listed in Table 6.
The firework articles mentioned in Table 6 are representative for all the 500 firework articles which are commercially obtainable for civilians, at the turn of the year in The Netherlands.

The rockets are also classified in hazard division 1.4S if they are packed in one of the UN-tested boxes which include an inner packaging of wire netting or glass wool. In both cases, an overlap of each side of at least 10 cm is necessary.
A special mark on the outside of the package of the rockets is recommended. This will avoid packaging mistakes and will optimize the control during transport.
If the rockets are packaged in UN-tested boxes without the inner packaging the hazard division will be 1.3G.

DISCUSSION

The expected hazard division for these kinds of firework articles is 1.4G and for some articles 1.3G and 1.4S. The classification of all the commercially obtainable fireworks in hazard division 1.4S can give rise to some discussion.

During the performance of test series 6(c), it was observed that the test procedure affects the classification result. For example, the wood fire of air-dried pieces of wood which are piled to form a lattice. This lattice behaves as a shelter for the propulsion of the rockets out of the fire. This influence is excluded by using the inner packaging of wire netting with firework articles with propulsion properties.
The irradiance of the used wooden stack is about 1.6 kW/m^2 at 15 m. The question is, whether the measured irradiance is cumulative for the wood fire and the explosive fire?
Another example is the influence of the smoke of the used liquid fuel, a mixture of diesel and petrol. This smoke around the fire shelters the irradiance. The quantification of the sheltering effect of the smoke is being researched at the present.
The mentioned influences bring test results into question if this is just within the limit of the criteria of a hazard division. TNO-PML plans to publish a report of these influences and to introduce these to the UN.

CONCLUSION

Common small firework articles, packed in UN-tested cardboard boxes are classified in UN hazard division 1.4S. The rockets must be packed with an inner packaging of wire netting for classification in UN hazard division 1.4S.

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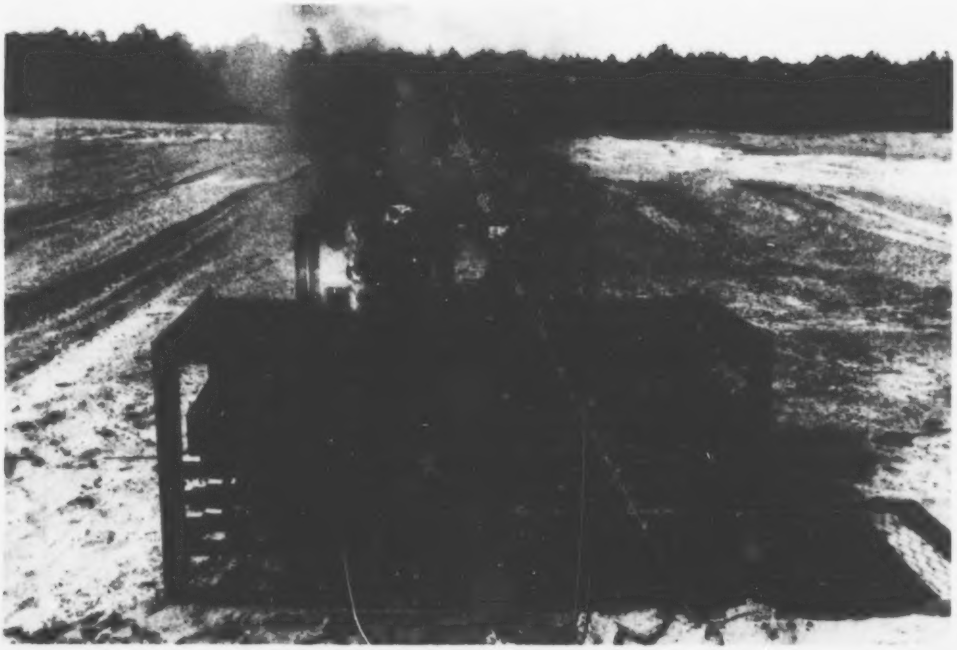

Figure 1 UN box with inner packaging after test series 6(c)

TABLES

Table 1 Ten firework families

Family type	Description
1 (cat A)*	Firecrackers, a single cracker containing not more than 2.5 g black powder per item. A string of firecrackers, containing maximal 25 g black powder per item and not more than 1 g black powder per compartment.
2 (cat B1)	Cylindrical fountain with light, smoke, report or whistling effect, or a combination of them. The cylindrical casing will not be ruptured during or after functioning. Maximum mass of pyrotechnic mixture is 40 g.
3 (cat B2)	See 2, with only light effect, sometimes called illuminating torch. Maximum mass of pyrotechnic mixture is 100 g. The explosion effects within 2 metres.
4 (cat C1)	Rockets, which will be ruptured by functioning. Maximum mass of pyrotechnic mixture is 25 g, of which 5 g black powder may be used for the report charge.
5 (cat C2)	Rotating, non rising fireworks. Maximum mass is 10 g of pyrotechnic mixture, of which 1 g black powder may be used for the report charge. Rupture of the materials is allowed.
6 (cat D1)	Rockets, which do not rupture when functioning. Maximum mass of pyrotechnic mixture is 25 g.
7 (cat D2)	Rotating, none rising fireworks. Maximum mass is 15 g of pyrotechnic mixture. Without rupture of the materials.
8 (cat D3)	Rotating, rising fireworks. Without rupture of the materials and the effects within 2 metres.
9 (cat E7)	Sparklers. Maximum mass of pyrotechnic mixture is 25 g.
10 (cat E)	Indoor fireworks, for example party poppers.

* type in accordance with the Dutch List of Small Fireworks

Table 2 Firework articles and recommended UN test series

Name	Code	Expl. mass (g)	Number of family	Test series recommended	Representative for famaly type(s)
Thunder	460	1.3	1	4 and 6	1
Lady cracker	k001b	25	1	4(b)	1 to 10[2]
Silver mine	k1801	40	2	4 and 6(a,c)	2/3/4/5/7/8/10
St.Helena Vol	0662	40	3	4 and 6	2/3/4/5/7/8/10
Star Rocket L.	t0520	23	6	6(a,c)	4/6
Ex.Ass.Rocket	t0578	17.5	4	4 and 6(a,c)	4/6
Sky Travel	k6600b	1	6	4	1 to 10[3]
Sparklers	no.20	9.7	9	6(c)	9
Assortment	-	-	-	6(c)	-
Traders distribution[1]			-	6(c)	-

[1] mix of all the firework articles mentioned in the table
[2] friction between fuses was tested
[3] thermal stability and sensitivity of pyrotechnic mixtures

Table 3 UN-tested cardboard boxes

Box type	Dimensions (m^3)	UN number
1	0.56 x 0.35 x 0.26	4G/Y31/S/--/NL/F.V.N.-VERMEY 764
2	0.60 x 0.35 x 0.35	4G/Y31/S/--/NL/F.V.N.-VERMEY 763
3	0.97 x 0.40 x 0.30	4G/Y33/S/--/NL/F.V.N.-VERMEY 762

Table 4 Data of the packed firework articles

Firework article	Code	Type of box	Number of art.	Mass of art.+box (kg)	Mass of expl. in box (kg)
Thunder	460	1	3000	27	3.9
Lady Cracker	k001b	1	274	27	10
Silver mine	k1801	2	82	10	3.28
St.Hel.Vol.	0662	2	96	10	3.84
Star rocket L.	t0520	3	108	12	2.48
Ex.Ass.rocket	t0560	2	378	12	6.24
Sky Travel	k6600b	1	2880	15	2.88
Sparklers	no.20	2	-	12	-
Assortment		2	12	15	-
Traders Distribution		2		15	-

Table 5 Measured results in test series 6(c)

Firework article	Fiery projections radius (m) >5	>15	Indentation of witness screen	Fire radius (m)	Irradiance at 15 m (W/m^2)
Thunder	0	0	none	8	*
St.Hel.Vol.	0	0	none	8	*
Silver Mine	0	0	none	9	1600
Star rocket (L)	13	4	none	8	*
Ex.Ass rocket	19	4	3	10	*
Sparklers	0	0	none	10	2400
Assortment	7	2	none	10	*
Trad.Distr.	0	0	none	10	*

* Irradiance value corresponding to the fire itself, the firework did not contribute to the irradiance. See value of Silver Mine

Table 6 Summary of the classified common small fireworks

Firework article	Code	Box type	Hazard division
Firecrackers		1	1.4S
Thunder	460		
Lady cracker	k001b		
Fountains, florals and parachutes		2	1.4S
St.Helena Volcano	0662		
Silver Mine	k1801		
Hand-held fireworks		2	1.4S
Sparklers	no.20		
Rockets*			1.4S
Star Rocket Large		3	
Exocet Rocket		2	
Sky Travel		1	
Assorted fireworks		2	1.4S
Assortment blister			
Trader distribution			

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* when packed in UN-tested box with inner packaging of wire netting or glass wool

APPENDIX I

EXAMPLE OF A DATA SHEET FOR COMMON SMALL FIREWORK ARTICLES

DATASHEET FIREWORKS

MANUFACTURER	FLOWER BASKET
NAME FIREWORK	LADY CRACKER 50
TYPE	FIRE CRACKER
NUMBER/CODE	K001

DIMENSIONS (CM/INCH)

LENGTH	WIDTH	HEIGHT	DIAMETER	OTHER
1.76			0.32	

CATEGORY IN LIST OF FIREWORKS	A	B1	B2	C	D	E
	X					

TOTAL MASS OF EXPLOSIVES (GRAM)	2.65

DEVIDED IN SPECIAL EFFECTS (GRAM)

LIGHT	SMOKE	BLACK POWDER	SOUND	BLAST	OTHER
		2.65			

CHEMICAL COMPOSITION

NAME	MASS (G)	PERC.
19 SULFUR		18
CARBON		15
16 POTASSIUM NITRATE		67

DESCRIPTION INERT MATERIALS	

FLOWER.BASKET BLADZIJDE 95

AERIAL SHELL DRIFT EFFECTS

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ABSTRACT

A prime consideration in determining separation distance requirements for aerial fireworks displays is where fallout of dangerous debris is likely to occur. Certainly the most dangerous single piece of fallout is a dud aerial shell. Thus it is important to have knowledge of where duds may fall during typical displays. This would be a relatively simple situation if aerial shells were ballistically stable, and they precisely followed the path determined by mortar orientation, shell muzzle velocity, and atmospheric conditions. Unfortunately, however, aerial shells tend to drift from their ideal (predicted) path, and that drift is greater than most realize. In order to determine where dud shells fall, a large number of aerial shells, both spherical and cylindrical, were fired into the air after having been rendered incapable of bursting at altitude. Most firings were from mortars that were positioned vertically and under calm wind conditions; however, some firings were from angled mortars. For spherical aerial shells, 7.6 cm to 25.4 cm (3 in to 10 in) it was found that, on average, duds fall 3.8 m per cm (32 ft per in) of shell size, from the point ballistically predicted. Further the data suggests that drifts as great as 12 m per cm (100 ft per in) of shell size may occur nearly 1 percent of the time. For cylindrical shells, 7.6 cm to 15.2 cm (3 in to 6 in) it was found that, on average, duds fall 2.4 m per cm (20 ft per in) of shell size, from the point ballistically predicted. Finally, a large number of 10.2-cm (4-in) cylindrical shells were fired in order to determine the effect of shell weight, shell length, and lift powder weight on drift distance.

INTRODUCTION

When aerial shells are fired from a mortar, fairly accurate predictions can be made about their ideal (average or typical) trajectories, providing the necessary input information is available. The type of information needed includes the shell's shape, weight, amount and type of lift, mortar tilt angle and azimuth, wind speed and direction. These ballistic predictions could be based on empirical data, but more often they are based on mathematical calculations [1,2,3]. The accuracy of the predictions generally improve with more and better input information. However, at present, the exact trajectory for an individual shell is not predictable. This is because, for each individual shell being fired, other needed input information is unknown or unknowable, and the mathematical models presently available lack the degree of sophistication to use the information even if it were known. For the purpose of this paper, the difference between the ballistically predicted path of an aerial shell and its actual path will be termed drift distance.

Knowledge of aerial shell drift distance is important in establishing appropriate spectator separation distances for fireworks displays. For example, if it were possible to align all of one's mortars so as to cause all shells to be propelled toward one specific fallout point, then it would be easy to avoid injuries from duds falling into the crowd. However, because individual shell drifts cannot be predicted, it is not possible to aim each mortar to compensate for drift. Thus, dud shells occurring during a show will be scattered about the fallout area. In establishing appropriate spectator separation distances, it is important to know how widely those duds are likely to be scattered.

The reason aerial shells drift or wander from their ideal trajectories is not completely known, at least by the authors. However, the cause of drift is of less concern than is its magnitude. The reason aerial shell drift is of more than mere academic interest, is that drift effects are considerably greater than many in the fireworks display business realize. This, in turn, means that appropriate spectator separation distances are greater than many realize. This paper summarizes information presented earlier by the authors [4,5] and others [6,7], and presents the results of new work by the authors and others [8].

BACKGROUND INFORMATION

MAGNUS EFFECT

While there may be many causes for aerial shell drift, it may be useful to discuss one cause as an example of how drift forces arise. Aerial shells generally tumble through the air after they are fired from a mortar. This tumbling (spinning) produces an effect analogous to that when a baseball pitcher throws a curve ball. The tumbling shell follows a trajectory which curves (drifts) away from that predicted based solely on mortar tilt and wind effects. This tumbling or curve-ball effect is technically known as the Magnus effect.

The magnitude of the drift derived from the Magnus effect depends on the rate of spin of the shell and its velocity through the air. To better understand why this is the case, consider Figure 1(A). Here a rotating aerial shell is depicted with air flowing past it. (From a physics standpoint this is the same as if the shell were moving through still air, but a stationary shell and the forces acting on it are easier to visualize and draw.) As the shell rotates, a thin layer of air, called the boundary layer, rotates along with the shell. When this air motion is combined with that moving past the shell, the resulting air velocity will not be the same on both sides of the shell. In effect, the two air motions add on the left side of the shell producing a higher overall velocity, and they subtract on the right side producing a lower velocity. Bernoulli's Principal states that the pressure in a moving column of fluid is inversely proportional to its velocity. Although not completely applicable in this case, it suggests that the pressure acting on the left side of the shell (P_1) will be less than that on the right side (P_2), see Figure 1(B). This pressure differential produces a net force (F) acting on the shell toward the left. This is the Magnus force, and it acts to push a rotating shell off course. The magnitude of the drift depends on the magnitude of the force and the length of time the force is applied. This depends on the combination of the shell's velocity through the air, its rate of spin, and the duration of the flight of the shell (with greater flight times resulting in greater drifts).

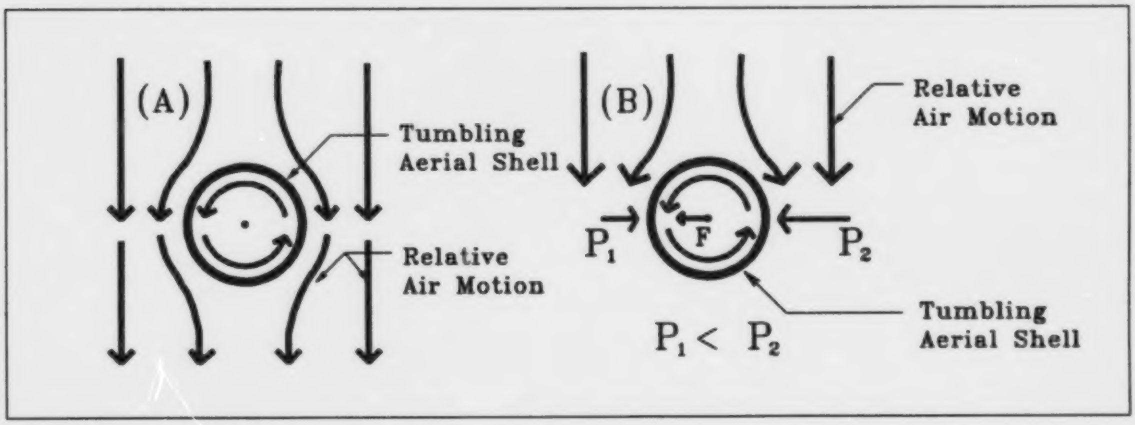

Figure 1. Rotating spherical aerial shell with air flowing past it, and the force produced as a result of pressure differential (P_2 - P_1).

MORTAR CHARACTERISTICS

The velocity of a shell and its time of flight depend (to some extent) on the characteristics of the mortar being used. For this reason, Table 1 gives characteristics of the mortars used in these tests and indicates on which shell drift tests they were used.

Table 1. Characteristics of Mortars Used in Aerial Shell Drift Tests.

Shell Size cm	(in)	Mortar Length[(a)] cm	(in)	Mortar I.D. cm	(in)	Mortar Material[(b)]	Type of Shell Fired Used
7.6	(3)	57.2	(22.5)	7.3	(2.89)	HDPE	All
10.1	(4)	56.9	(22.4)	9.9	(3.88)	HDPE	Spherical
10.1	(4)	61.0	(24.0)	10.4	(4.10)	HDPE[(c)]	Cylindrical
12.7	(5)	68.6	(27.0)	12.5	(4.92)	HDPE	All
15.2	(6)	68.6	(27.0)	15.0	(5.91)	HDPE	Spherical
15.2	(6)	75.7	(29.8)	15.5	(6.10)	Steel	Both
20.3	(8)	98.6	(38.8)	20.3	(8.00)	Steel	Spherical
25.4	(10)	118.9	(46.8)	25.6	(10.06)	Steel	Spherical

(a) Mortar length is measured from the top of the mortar plug to the mouth of the mortar.
(b) HDPE = High Density Polyethylene.
(c) Mighty-Mite mortar with a slightly tapering ID. Reported ID is an average.

ELEVATION ABOVE SEA LEVEL

Another factor possibly influencing drift distance is air density, which primarily depends on the elevation above sea level at which shells are fired. As air density decreases, so does the magnitude of forces acting on the shell; drift forces will be less, but so will aerodynamic drag (which means the flight time of shells will be greater). The combined effect of increased elevation is to have a smaller drift force acting for a longer time. At the time of writing this paper, the authors have not evaluated the precise net effect of changes in elevation; however, it is felt that any elevation dependence is small.

(Except as noted, the tests reported here were conducted in Whitewater, CO at approximately 4600 ft above sea level.)

ABSOLUTE DRIFT PREDICTIONS

The speed of an aerial shell as it leaves the mortar and then travels through the air is fairly predictable based on calculations using typical shell parameters [1,2], or it can be measured [9,10]. However, as suggested in the introduction, the magnitude and orientation of a shell's drift are not absolutely predictable. In part, this is because no one has developed an adequate mathematical model. However, more importantly, when a shell is fired, one does not have details of the shell's exact position in the mortar, the shell's internal mass distribution, the smoothness and symmetry of the shell's surface and the mortar's interior, etc., all of which would be needed to perform a drift calculation (assuming an appropriate mathematical model existed). For this reason, it may never be possible to calculate drift distance for an individual shell. As an alternative it is possible to measure typical aerial shell drifts; then to use this information in a general way to predict the average drifts of shells to be fired. However, it must be recognized that those predictions will only be accurate in a statistical sense. For example, it might be possible to state for a given type of shell, that 5% of the time it will drift between 30 and 60 meters in a direction between north and east. Similarly, the likelihood for other drifts could be stated. However, for any particular shell, it is not possible to predict the precise magnitude or direction of its drift. For this reason, drift distances reported in this paper can only be stated in a statistical or probabilistic sense.

EXPERIMENTAL METHOD

SHELL FIRINGS

Except in a few cases, the only mortar orientation used in this study was vertical. Also, tests were generally performed under calm surface wind conditions, i.e. winds measured at 6.1 meters (20 ft) above ground were less than 3.2 km/h (2 mph). Both spherical and cylindrical shells were tested. The spherical aerial shells were commercially produced and ranged in size from 7.6 cm (3 in) to 25.4 cm (10 in). Before being fired, the shells were altered so as not to burst during their flight, i.e. they were made into duds. (In most cases this was accomplished by injecting water into each shell's time fuse.) Also, a variety of shells from different manufacturers were used, so that the results would tend to be independent of peculiarities of any one manufacturer. (The brands or manufacturers used were Onda, Yung Feng, Horse, Temple of Heaven, and Flying Dragon.) The shells were fired using an electric match to replace the quick match shell leader installed by the manufacturer. All the cylindrical shells were specifically made for these tests and were inert. They ranged in size from 7.6 cm (3 in) to 15.2 cm (6 in). These shells were also fired electrically.

Each test consisted of the firing of from 8 to 10 shells of one size. After firing and upon the shell's return to ground, the approximate point of impact of each shell was noted. Following the completion of firing of a series of shells of one size, the exact points of impact were determined relative to a coordinate grid system. This process is illustrated in Figure 2(A).

DATA REDUCTION

If one could be assured that experimental conditions were ideal (perfect mortar alignment and absolutely no wind from the surface through the maximum height reached by the shell), there would be little data processing to perform. For each shell size, it would only be necessary to calculate the average displacements from the mortar, their standard deviation and standard error, as illustrated in Figure 2(B).

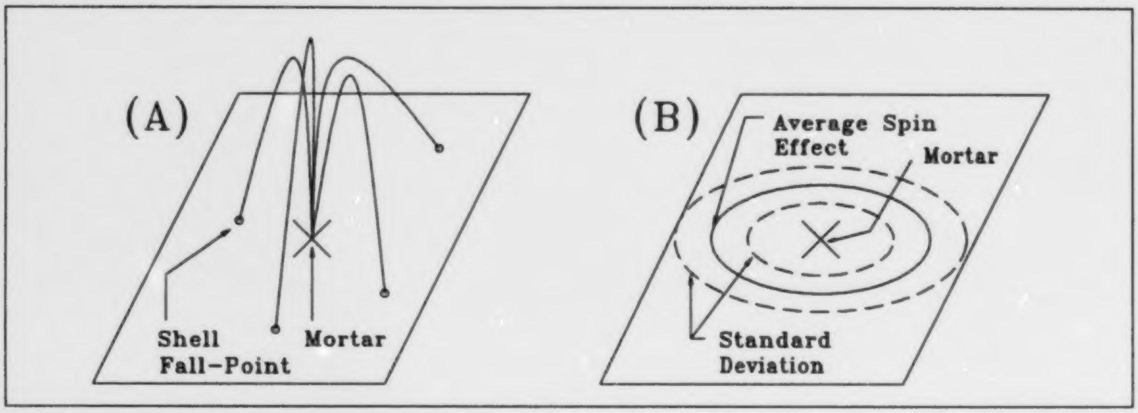

Figure 2. Method of determining aerial shell drift distance.

Unfortunately, conditions were not perfect; for example, there were usually winds aloft that pushed the shells somewhat off course. Accordingly, some mechanism was needed to separate systematic effects (such as winds aloft) from the randomly oriented shell drift effects. It was decided to shift the original coordinate grid in order to correct for systematic errors. This was accomplished by first calculating the mathematical center for the distribution of shell impact points and then assigning that as the origin of a new (shifted) coordinate system. In effect, what that does is to say that the distribution of shell impact points in the shifted coordinate system is the distribution that would have occurred had there not been systematic errors.

If the tests for each type of aerial shell had included many shells, and if one could be certain that wind conditions did not change during the tests, then this grid adjustment method should work very well. However, in this study, only a limited number of shells were used and wind conditions probably did change at least a little during the time it took to fire the shells. Thus there is some uncertainty as to how accurately the impact points in the shifted coordinate system represent actual shell drift effects. Having given this matter considerable thought, the authors feel that the average drifts presented in this paper probably are slightly under-estimated, while the reported standard deviations probably are slightly over-estimated. (For a more complete discussion of this subject, see Notes A and B of reference 4.)

Figure 3 and Table 2 illustrate the process for the first set of shells fired, 15.2-cm (6-in) spherical shells. The mortar was placed at the origin of the coordinate system, indicated by the large X in Figure 3. The points of fall of the shells fired are indicated as small circles, which are located primarily in the southwest quadrant. The center of the pattern of these points, the average displacements, was determined to be 31.4 m (103 ft) south and 34.7 m (114 ft) west and is indicated as the smaller x in Figure 3. Next, for each point of fall, the distance from the center of the pattern was determined and the average of those distances was calculated. In the case of these 15.2-cm (6-in) spherical shells, the average is 44.2 m (145 ft) and is shown as the heavy solid line circle in Figure 3. [Note that in this initial test series an error had been made in the vertical positioning of the mortar. That is the primary reason for the center of the fall points being located about 47 m (154 ft) from the mortar.]

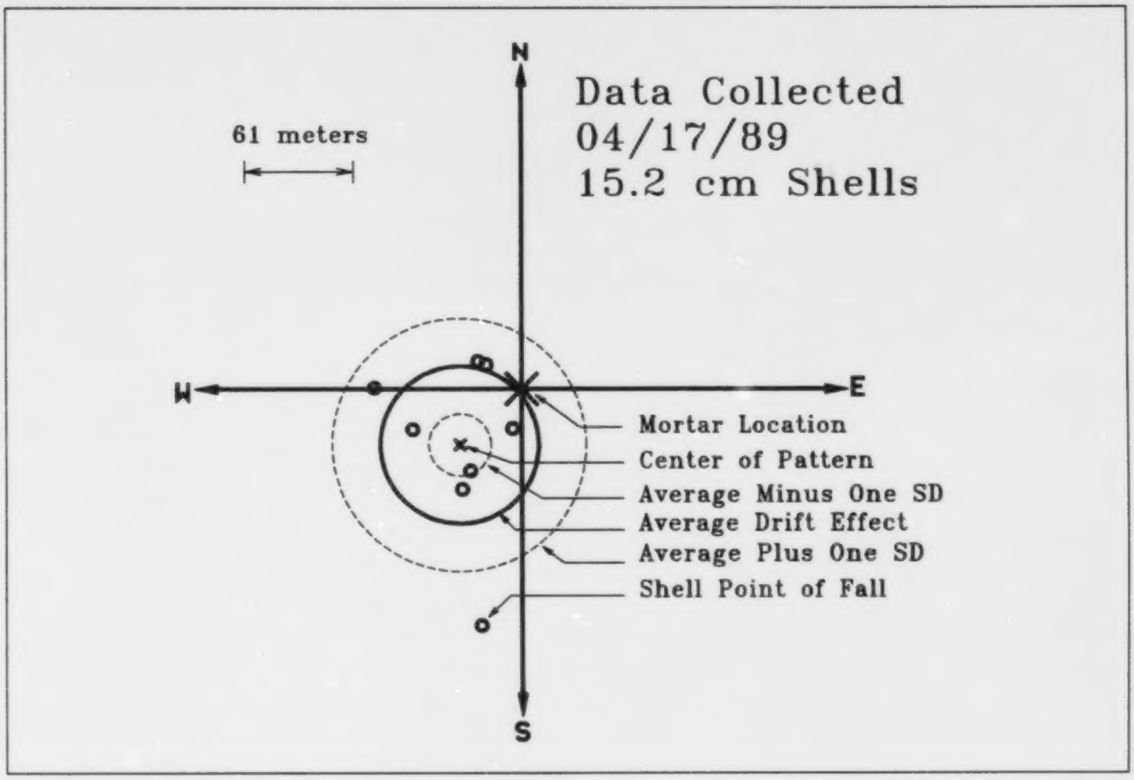
N
S
E
W
61 meters
Data Collected
04/17/89
15.2 cm Shells
Mortar Location
Center of Pattern
Average Minus One SD
Average Drift Effect
Average Plus One SD
Shell Point of Fall

Figure 3. Illustration of 15.2-cm (6-in) spherical aerial shell drift distance determination.

Table 2. 15.2-cm (6-in) Spherical Shell Drift Effect Data.

Shell No.	Shell Displacement from Mortar (m) North	Shell Displacement from Mortar (m) East	Shell Displacement in Shifted Grid (m) North	Shell Displacement in Shifted Grid (m) East	Distance from Center (m)
1	-22.9	-61.0	8.5	-26.2	27.4
2	0.6	-82.4	30.0	-47.6	57.3
3	15.6	-24.7	47.0	10.1	48.2
4[a]	---	---	---	---	---
5	-46.1	-29.0	-14.6	5.8	15.9
6	-56.4	-33.6	-25.0	1.2	25.0
7	13.7	-20.1	45.1	14.6	47.6
8	-132.7	-22.9	-101.3	11.9	101.9
9	-22.3	-5.2	9.2	29.6	31.1
Average	-31.4	-34.8	≈0	≈0	44.2

(a) Shell burst at altitude, thus no drift data was produced.

pendent of shell size, the data from all shells fired could be used by standardizing the results for each of the groups. (This is a reasonable assumption, but not one that is assured.) To accomplish this standardization, each individual shell drift was expressed as a percent of the mean (average) for that size shell, as determined previously by a linear least squares fit of all the data. The standardized drift results for all 75 shells were then divided into twelve class intervals as shown in Table 4.

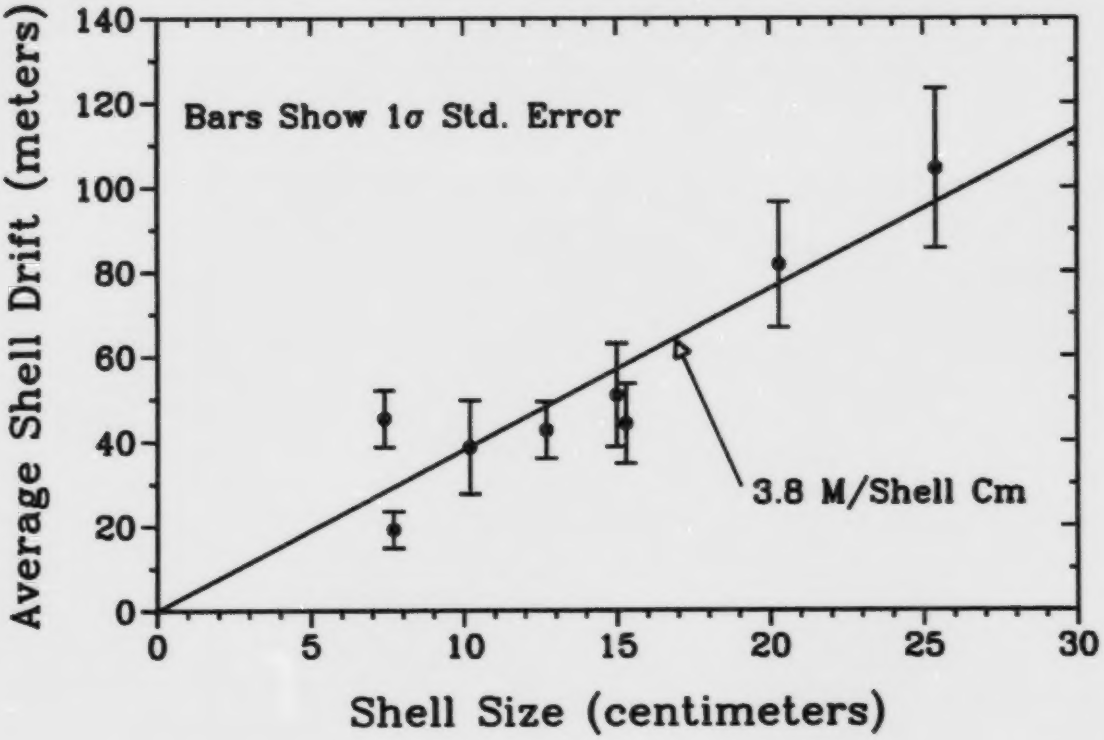

Figure 4. Average spherical aerial shell drift distance as a function of shell size.

Figure 5 is a plot of the cumulative frequency of the standardized drift distances, against upper class interval limits, on linear probability paper. The appearance of such a graph gives an indication of the nature of the statistical distribution. For example, a statistically normal distribution would appear as a straight line. Other distributions, such as log-normal, appear as curves unless plotted using a log axis. When a distribution is normal bi-modal, it appears as two straight line segments with different slopes. The distribution of aerial shell drift distances in Figure 5 has the appearance of two normal distributions, with the break occuring at the average shell drift distance. Thus from Figure 5, it can be seen that nearly 65% of the time shell drifts will be less than the mean, and that shell drifts as great as about 300% of the mean will occur about 1% of the time. In Table 4, it can be seen that the shells with the greatest relative drifts were for 7.6-cm (3-in) and 10.2-cm (4-in) shells. Thus it is possible that only the smaller sized shells experience such extreme drifts. Unfortunately, the present collection of data is not sufficiently large to allow that to be established with certainty.

Table 4. Standardized Spherical Shell Drift Data by Class Interval.

Shell Size cm	(in)	Class Intervals (Percent of Mean Drift for Each Shell Size)											
		0-25	25-50	50-75	75-100	100-125	125-150	150-175	175-200	200-225	225-250	250-275	275-300
7.6	(3)	3	2	0	2	2	1	0	0	0	0	0	0
7.6	(3)	0	0	1	3	1	0	0	2	1	1	1	0
10.2	(4)	0	5	1	0	1	1	0	0	1	0	0	1
12.7	(5)	1	1	1	3	2	1	1	0	0	0	0	0
15.2	(6)	0	3	2	2	0	0	1	0	0	0	0	0
16.2	(6)	1	1	3	1	0	0	1	1	0	0	0	0
20.3	(8)	0	1	4	2	0	0	1	1	0	1	0	0
25.4	(10)	0	1	3	1	0	2	1	0	1	0	0	0
Totals		5	14	15	14	6	5	5	4	3	2	1	1
Cum. Tot.		5	19	34	48	54	59	64	68	71	73	74	75
Cum. %		7	25	45	64	72	79	85	91	95	97	99	100

10.2 CM (4 IN) CYLINDRICAL SHELLS, AVERAGE DRIFT DISTANCES

With cylindrical shells, length as well as diameter plays a role in determining drift distances. Also, shell mass and lift powder amounts can vary significantly with shell length. For this reason, the study of cylindrical shells was begun with a rather lengthy examination of the effects of shell length, shell mass, and lift amount for 10.2-cm (4-in) shells. All of the shells used in this effort were plastic (so-called RAP Shells) with relatively smooth exterior surfaces, 9.2 cm (3.62 in) in diameter, without lift-cup, and using 2F-A blasting black powder. Table 5 is a listing of the shell parameter values and the average drift distance for each group of ten shells fired.

In order to determine the functional relationship between drift distance and the various shell parameters, multivariate analysis was performed [9]. Although 33 sets of 10 shells were fired in this test series, this is not a particularly large number considering the variability in the results and number of shell variables. Thus, it would be preferable to seek only linear relationships between drift distance and the shell variables. However, only for moderate amounts of lift powder is the relationship essentially linear; at low amounts of lift (2% or 3% of shell mass), drift distance falls very rapidly to near zero. In order to incorporate this effect, an additional (composite) variable, incorporating both shell lift and mass, was introduced into the multivariate analysis. The regression formula fitted in the analysis was

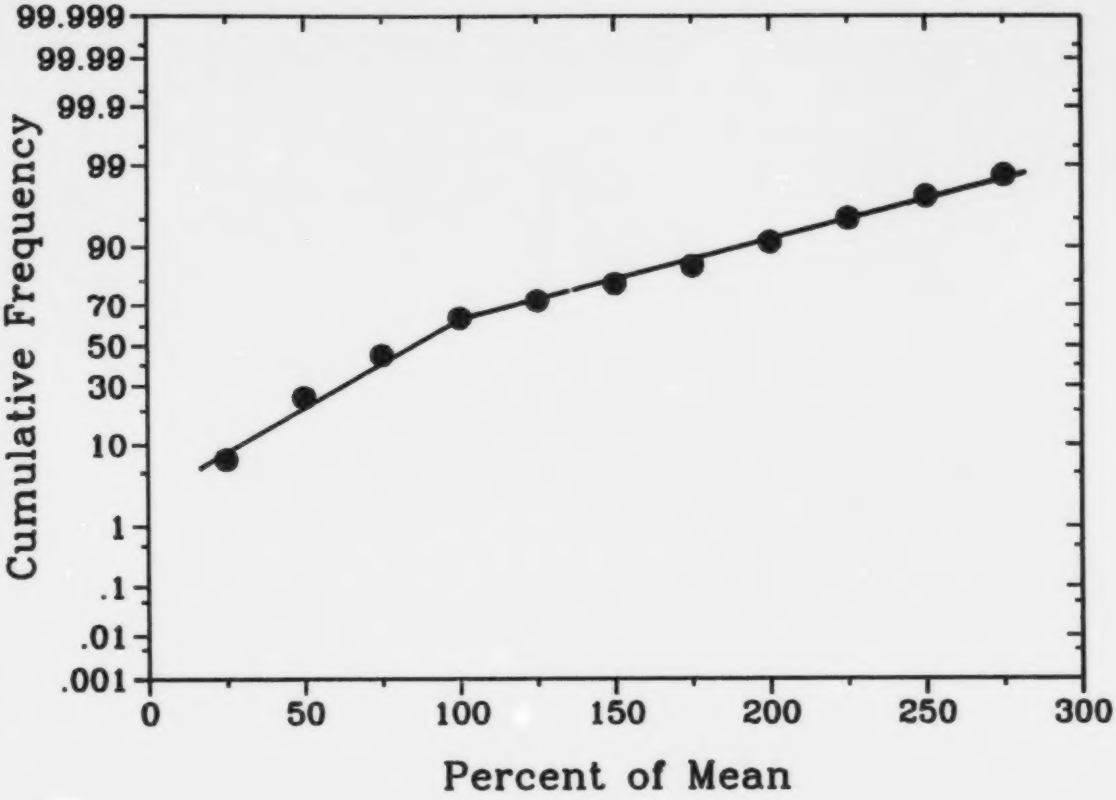

Figure 5. Cumulative frequency as a function of standardized spherical shell drift.

Equation [1]

$$D_d = a + b \cdot M_s + c \cdot L_s + d \cdot M_l + e/(M_l - 0.03 \cdot M_s), \text{ where,}$$

D_d = drift distance in m (ft),
M_s = shell mass in gm (oz),
L_s = shell length in cm (in),
M_l = lift amount in gm (oz), and
a,b,c,d and e are constants.

The constants, as determined by multivariate analysis, are:

$a = 16.4$ m (54 ft)

$b = -0.0075$ m/gm (-0.69 ft/oz)

$c = -0.36$ m/cm (-3.0 ft/in)

$d = 0.21$ m/gm (18 ft/oz)

$e = -99$ m/gm (9100 ft/oz).

The correlation coefficient for the multivariate regression is 0.86, which indicates quite a good fit of the data to Equation 1. (Note that a perfect fit would have produced a correlation coefficient of 1.00.) As an indication of the uncertainty in drift distance predictions made using Equation 1, it should be noted that the average deviation between the experimental results and predicted value was 22 percent.

Table 5. Shell Parameter Values and Drift Distance for 10.2-cm (4-in) Cylindrical Shells.

Group Number	Shell Parameters							
	Shell Mass		Shell Length		Lift Mass		Drift Distance	
	g	(oz)	cm	(in)	g	(oz)	m	(ft)
1	250	(8.8)	7.6	(3.0)	25	(0.9)	10.6	(34.7)
2	250	(8.8)	7.6	(3.0)	38	(1.3)	20.2	(66.1)
3	250	(8.8)	7.6	(3.0)	50	(1.8)	27.5	(90.1)
4	250	(8.8)	7.6	(3.0)	75	(2.6)	35.2	(115.)
5	250	(8.8)	7.6	(3.0)	100	(3.5)	37.6	(123.)
6	250	(8.8)	15.2	(6.0)	38	(1.3)	7.8	(25.5)
7	250	(8.8)	15.2	(6.0)	75	(2.6)	13.6	(44.7)
8	250	(8.8)	30.5	(12.0)	38	(1.3)	9.1	(29.9)
9	250	(8.8)	30.5	(12.0)	75	(2.6)	13.0	(43.0)
10	500	(17.6)	7.6	(3.0)	25	(0.9)	3.8	(12.6)
11	500	(17.6)	7.6	(3.0)	38	(1.3)	13.3	(43.6)
12	500	(17.6)	7.6	(3.0)	50	(1.8)	11.2	(36.8)
13	500	(17.6)	7.6	(3.0)	50	(1.8)	19.5	(63.9)
14	500	(17.6)	7.6	(3.0)	50	(1.8)	17.9	(58.8)
15	500	(17.6)	7.6	(3.0)	50	(1.8)	21.4	(70.0)
16	500	(17.6)	7.6	(3.0)	50	(1.8)	17.2	(56.4)
17	500	(17.6)	7.6	(3.0)	75	(2.6)	25.4	(83.4)
18	500	(17.6)	7.6	(3.0)	100	(3.5)	32.1	(105.)
19	475	(16.8)	15.2	(6.0)	38	(1.3)	8.9	(29.4)
20	475	(16.8)	15.2	(6.0)	50	(1.8)	14.0	(46.0)
21	475	(16.8)	15.2	(6.0)	75	(2.6)	20.5	(67.4)
22	475	(16.8)	15.2	(6.0)	75	(2.6)	13.6	(44.6)
23	475	(16.8)	15.2	(6.0)	100	(3.5)	27.6	(90.5)
24	500	(17.6)	30.5	(12.0)	38	(1.3)	9.5	(31.3)
25	750	(26.5)	22.8	(9.0)	38	(1.3)	4.7	(15.4)
26	750	(26.5)	22.8	(9.0)	75	(2.6)	14.5	(47.6)
27	925	(32.6)	7.6	(3.0)	50	(1.8)	11.4	(37.4)
28	925	(32.6)	7.6	(3.0)	100	(3.5)	18.6	(61.0)
29	1000	(35.2)	15.2	(6.0)	50	(1.8)	9.0	(29.5)
30	1000	(35.2)	15.2	(6.0)	100	(3.5)	24.8	(81.6)
31	980	(34.6)	30.5	(12.0)	50	(1.8)	7.2	(23.6)
32	980	(34.6)	30.5	(12.0)	75	(2.6)	15.4	(50.5)
33	980	(34.6)	30.5	(12.0)	100	(3.5)	20.1	(66.0)

If it is assumed that a typical 10.2 cm (4 in) cylindrical shell weighs 454 g (16 oz), is 8.9 cm (3.5 in) long, and uses 54 g (1.9 oz) of lift powder, Equation 1 predicts the average drift distance to be 18.7 m (61.3 ft). As shell weight, length and lift amount are varied, the average drift distance should change as suggested by the constants b through e above. Figures 6A through 6C demonstrate the expected result of varying these shell parameters.

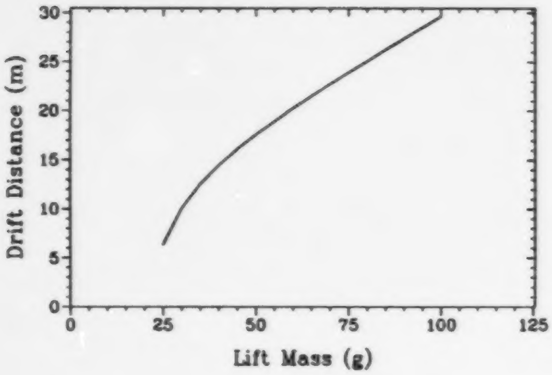

Figure 6A. Effect of varying lift powder mass for a typical 10.2-cm (4-in) cyl. shell.

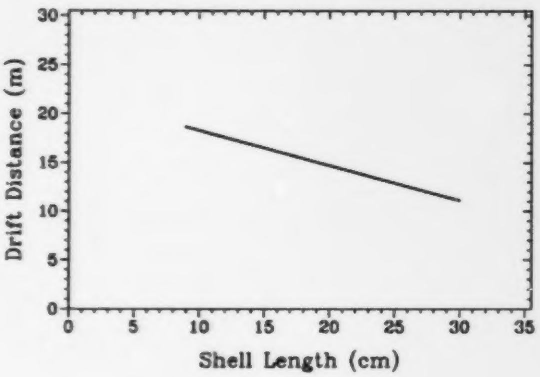

Figure 6B. Effect of varying shell length for a typical 10.2-cm (4-in) cylindrical shell.

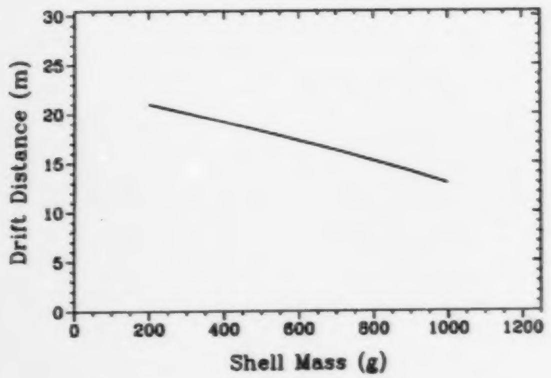

Figure 6C. Effect of varying shell mass for a typical 10.2-cm (4-in) cylindrical shell.

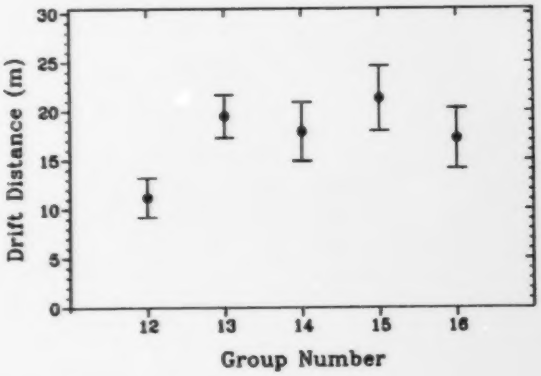

Figure 7. Reproducibility of results from five groups of ten identical 10.2-cm (4-in) cylindrical shells.

DRIFT DISTANCE REPRODUCIBILITY

In a brief discussion of aerial shell drift experiments, Shimizu reports [12] that significantly different test results were observed on different occasions. Specifically, he observed that the scatter of dud shells was about twice as great on one occasion as it was on another. He speculated that a possible reason for this might have been turbulent air currents experienced on one of the days.

The authors also observed a similar situation; a second set of measurements were made on 7.6-cm (3-in) spherical shells because results from the first set was unexpectedly high. The two sets of drift distances differed by more than a factor of two. This was enough greater than the calculated standard errors (see Figure 4), to suggest that the difference may not be the result of a random statistical occurrence. A brief attempt was made to look at this further. Five identical groups of shells, numbers 12 through 16 in Table 5, were fired on five different days. Figure 7 displays the average drift distances for these five measurements, along with their standard errors. Again there is about a factor of two in the spread of the data. However, considering the standard errors, one cannot be certain that the difference was more than a random statistical occurrence.

CYLINDRICAL SHELLS, AVERAGE DRIFT DISTANCE

In addition to the drift distance for 10.2-cm (4-in) cylindrical shells, data was also collected for 7.6-, 12.7-, and 15.2-cm (3-, 5-, and 6-in) shells. These too were inert shells made especially for testing. Varying shell parameters significantly effects drift distance, thus information on shell diameter, shell length, shell mass and mass of 2 F-A lift powder was included in Table 6 along with the results of drift distance measurements.

Table 6. Shell Parameter Values and Drift Distances for Cylindrical Shells.

Shell Diameter		Shell Length		Shell Mass		Lift Mass		Drift Distance	
cm	(in)	g	(in)	cm	(oz)	g	(oz)	m	(ft)
6.7	(2.62)	6.9	(2.7)	180	(6.5)	28	(1)	20	(64)
6.7	(2.62)[a]	6.9	(2.7)	180	(6.5)	28	(1)	15	(49)
9.2	(3.62)[b]	8.9	(3.5)	460	(16.)	56	(2)	190	(63)
11.4	(4.5)	10.2	(4.0)	910	(32.)	84	(3)	30	(98)
11.4	(4.5)[a]	10.2	(4.0)	910	(32.)	84	(3)	36	(120)
14.1	(5.56)	12.7	(5.0)	1800	(64.)	75	(2.7)	22	(72)
14.1	(5.56)	12.7	(5.0)	1800	(64.)	100	(3.6)	36	(120)
14.1	(5.56)	12.7	(5.0)	1800	(64.)	130	(4.5)	58	(190)
14.1	(5.56)	12.7	(5.0)	1800	(64.)	130	(4.5)	49	(160)

[a] These shells were fired from non-vertical (tilted) mortars.

[b] Typical shell parameters and calculated drift distances using Equation 1.

Table 6 reports results for a series of 15.2-cm (6-in) shell tests, using varying amounts of lift powder. The observed drift distances follow a relationship similar to that shown in Figure 6A. If it is assumed that the typical amount of lift used for 15.2-cm (6-in) cylindrical shells, with other parameters as listed in Table 6, is 112 g (4 oz) then the expected drift distances will be about 43 m (140 ft). This result and the others reported in Table 6 are plotted in Figure 8, and have the appearance of a roughly linear relationship with a slope of approximately 2.4 m per cm (20 ft per in) of shell size.

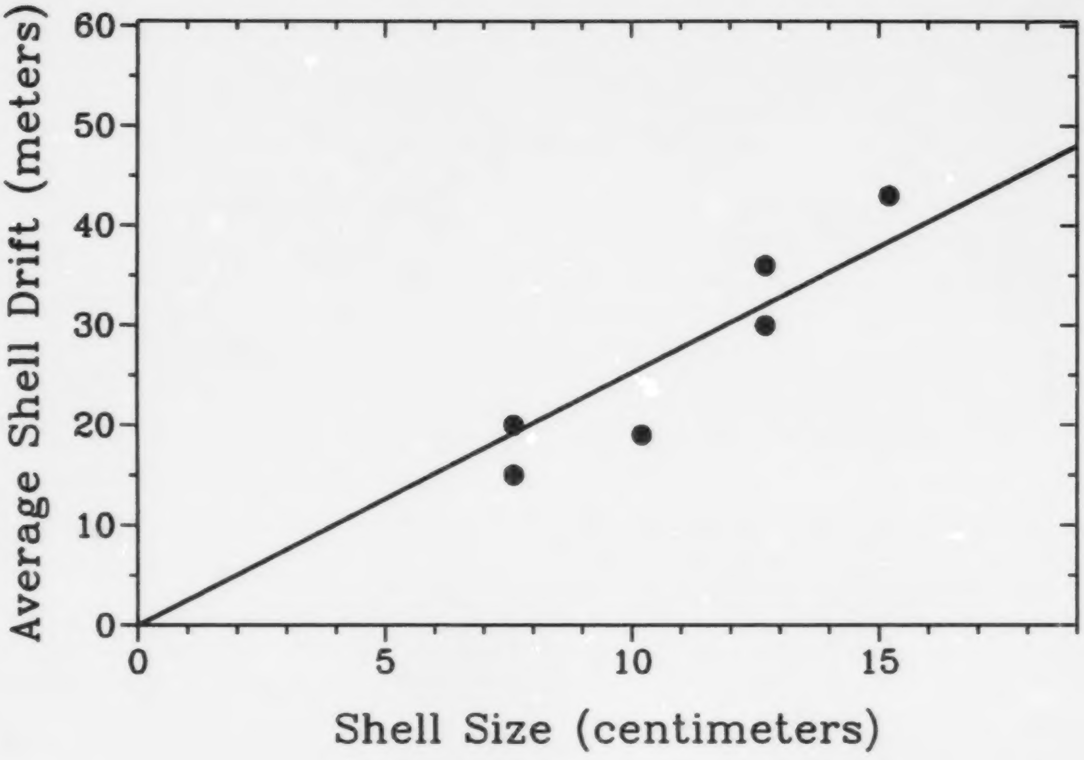

Figure 8. Average cylindrical aerial shell drift distance as a function of size.

COMPARISON WITH THE RESULTS OF OTHERS

Approximately 30 years ago T. Shimizu, working at the request of Professor S. Yamamoto at Tokyo University [6,7], studied the drift of spherical aerial shells for the purpose of determining appropriate separation distances. In order to simulate typical conditions, many of the measurements were made using mortars angled to about 10° and in many cases a significant wind was blowing. In some tests, efforts were made to restrict the normal spin of the shells after firing, and the grid adjustment method used in this study was not employed. Thus although they were excellent studies, most of the data is not directly comparable with the results of this study. However, Table 7 presents the results from those cases that are the most comparable.

On average, the drift distance results of Yamamoto (Shimizu) are about 5 percent greater than those predicted from this study. Considering the differences between the two bodies of work, this is amazingly good agreement and serves to increase the authors' confidence in their results.

Table 7. Comparison of the Yamamoto Spherical Shell Drift Results with Those of This Study.

Conditions	Drift Distance m	(ft)	This Study's Results m	(ft)	Difference
5 Light Shells with smoke candle attached (wind = 0.7 m/s) (size = 3 in)	25.0	(82)	29.3	(96)	-15%
5 Heavy Shells with smoke candle attached (wind = 0.7 m/s) (size = 3 in)	38.9	(128)	29.3	(96)	+33%
15 Heavy Shells with smoke candle attached (wind = 0.7 m/s) (size = 3 sun)	35.8	(117)	35.1	(115)	+2%
15 Light Shells with smoke candle attached (wind = 2 m/s) (size = 3 sun)	39.9	(130)	35.1	(115)	+13%
15 Heavy Shells with smoke candle attached (wind = 2.5 m/s) (size = 5 sun)	54.2	(178)	58.5	(192)	-7%

Note that 1 sun = 3 cm (1.2 in).

In 1989, E. Contestabile, at the Canadian Explosives Research Laboratory, conducted a series of aerial shell ballistics tests[8]. Only 15.5-cm (6-in) shells were used. They weighed 1340 g (48 oz) and were fired from a 4-m (13-ft) long mortar using 42.5, 56.7 or 99.1 g (1.5, 2.0, or 3.5 oz) of lift powder. The shells were of an unusual geometry, having a relatively short cylindrical wall and domed ends, one end having a concave recess to contain the lift charge. Thus it would be anticipated that the drift distances for these intermediately-shaped shells might be somewhere between those reported here for spherical and cylindrical shells. The results from the Contestabile tests are listed in Table 8.

Table 8. Contestabile Shell Drift Results.

Lift Weight g	(oz)	Number of Shells Fired	Drift Distance m	(ft)
42.5	(1.5)	7	11.8	(39)
56.7	(2.0)	7	28.2	(93)
99.2	(3.5)	12	53.5	(176)

In order to compare Contestabile's data with the results from this study, it is necessary to adjust for what would be expected for a more typical 15.2-cm (6-in) cylindrical shell. In the present study this was considered to be a shell weighing about 1800 g (64 oz) and using 112 g (4.0 oz) of lift powder. Based on the effect of shell mass and lift observed for 10.2-cm (4-in) shells, and the effect of lift mass for 15.2-cm (6-in) shells observed in this study, the authors estimate that Contestabile would have observed a drift distance of about 46 m (150 ft) for such shell and lift mass. This compares well with the prediction from the present study of 58 m (190 ft) for spherical shells and 36 m (120 ft) for cylindrical shells, particularly when it is recalled that the Contestabile shells were expected to experience drifts somewhere between those for cylindrical and spherical shells.

EFFECT OF MORTAR TILT ON DRIFT DISTANCE

On three occasions, groups of the same size shells were fired from both vertical and tilted mortars. This brief study was conducted to discover the approximate magnitude of any strong dependence of shell drift distance on mortar tilt angle. Table 9 lists the results of this study. Although some differences were observed, the results are not consistent. Thus it would seem that if there is a dependency of drift distance on mortar tilt angle, the effect is too small to have been observed in this brief study.

Table 9. Effect of Mortar Tilt on Drift Distance.

Shell cm (in)	Shell Shape	Mortar Tilt Angle (°)	Drift Distance m (ft)	Difference
7.6 (3)	Cyl.	0	19 (64)	
		15	15 (49)	- 23%
12.5 (5)	Cyl.	0	30 (98)	
		10	36 (119)	+ 21%
15.2 (6)	Sph.	0	44 (146)	
		24	30 (167)	+ 15%

DISCUSSION

In research there always seems to be more data that could (should) be collected. However, the data collected to date are probably sufficient and should be used to consider the important question of the adequacy of spectator separation distances. Unfortunately, doing that is more complex than might at first be realized. For example, it involves making assumptions about such things as:

- How accurately can a typically-skilled display operator predict the ideal trajectory of aerial shells?
- How precisely can a typically-skilled display operator align his mortars?
- To what extent will mortar alignment change during firing?

— How different are winds aloft likely to be than those experienced at ground level, which were considered in deciding how the mortars should be aimed?

— What percentage of dud shells falling outside the secured boundary is acceptable, recognizing that choosing 0% would probably require about 18 m per cm (150 ft per in) of shell size?

Because of these complexities, a discussion of appropriate spectator separation distances is beyond the scope of this article. Hopefully, the authors or others will soon undertake this important task.

Another area of application for the results reported here is in statistically predicting the trajectory of aerial shells. Armed with information about drift distances, it is possible to use a relatively simple computer model to predict the average trajectory of aerial shells and then superimpose on those results the empirically determined and statistically distributed drift distances [3]. This has been performed in a number of cases to determine the likelihood of various accident scenarios.

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REPEAT FIRING OF 10.2 cm (4 in), SDR-17, HDPE MORTARS

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ABSTRACT

High Density Polyethylene (HDPE) mortars are beginning to find wide use because of their desirable characteristics. They are relatively inexpensive, light weight, have a long service life, and some consider them to be among the safest mortars presently in use. Initially HDPE mortars were only recommended for use in electrically fired displays, where each mortar is fired only once. This was done because of a desire to take a cautious approach with this relatively new mortar material, even though the mortars had successfully passed some repeat firing tests. Now, it is becoming increasingly common to use HDPE mortars for manually discharged displays, in which individual mortars are fired repeatedly. The mortars heat up during firing, and, being a thermoplastic, they lose strength with increasing temperature. If mortar temperature rises sufficiently high, they will burst during use, venting the lift gases needed to propel shells to safe altitudes. To date there has been no systematic study of HDPE mortars under conditions of repeat firings, in order to determine the safe limits for their use. Thus it is appropriate to more carefully examine the performance of HDPE mortars under conditions of repeat firing and to offer guidance for their use. Measurements were made of the thermal energy deposited in a mortar during the process of firing 10.2 cm (4 in) aerial shells and of the distribution of that thermal energy along the length of mortars for typical aerial shell firings. Then, measurements were made of the rate of heat dissipation from HDPE mortars freely exposed to air and when buried in dry sand. Finally, data was collected regarding the ability of HDPE mortars to survive shell firings as a function of temperature. With this information, very rough guidelines are proposed for repeat firing of thick-walled, 10.2 cm (4 in), SDR-17, HDPE mortars.

INTRODUCTION

The use of High Density Polyethylene (HDPE) for fireworks mortars has been independently discovered by several individuals around the world. For example, S. Howard of Australia sets the date of his first use sometime before 1970 [1], R. Lancaster of Great Britain reports his use as beginning about 1976 [2], and P. Spielbauer and the authors first use in the United States dates to about 1985 [3]. However, most people in the fireworks industry were probably unaware of the potential of HDPE mortars until articles describing their use began to appear in the mid to late 1980s [4,5,6].

Initially the authors limited their endorsement of HDPE mortars to use in electrically fired displays, where each mortar fires only once during a show. Since then, the use of HDPE mortars has become fairly widespread, and they are now being used with increasing frequency in manually fired displays. With repeated shell firings over a short interval, the mortar's interior surface can heat to temperatures exceeding 100°C (212°F). Since it is known that the strength of HDPE falls with increasing temperature, at some temperature, the mortar's strength must fall to an unacceptably low value. At that point, use of the mortar must be interrupted until the mortar cools to a sufficiently low temperature.

In an attempt to determine the safe operating temperature for HDPE mortars and to set guidelines for their use when fired repeatedly, the authors undertook the present study. However, in order to limit the scope, the initial work has only been to establish the experimental method to be used in future studies and to briefly examine repeat firing of 10.2 cm (4 in) mortars with fairly thick walls (pipe with an SDR of 17). It is anticipated that the present work will soon be expanded and will include other wall thickness and other mortar sizes.

BACKGROUND INFORMATION

Aerial shells are propelled from a mortar because of the gas pressure produced by burning the black powder lift charge. It is the function of the mortar to successfully contain these high pressures while the shell is being discharged. Ignoring end effects, a pipe's strength is a function of its wall thickness, the tensile strength of the material from which it is constructed and the inside diameter of the pipe. This functional relationship is shown in Equation 1 [7,8]:

Eq. 1 $P_b = 2 \cdot S_t \cdot t_w / d_i$ where,

P_b is burst strength (pressure),

S_t is tensile strength of the pipe material,

t_w is wall thickness, and

d_i is the inside diameter of the pipe.

From Equation 1, it is apparent that burst strength for a pipe is proportional to its wall thickness. Thus it is appropriate to consider the wall thickness for typical 10.2 cm (4 in), HDPE mortars; these are listed in Table 1.

Table 1. Wall Thickness for Typical 10.2 cm (4 in), HDPE Mortars.

Source - Designation	Minimum Specified Wall Thickness cm	(in)	Typical Wall Thickness[c] cm	(in)
Commercial Pipe - SDR = 17[a]	0.67	(0.26)	0.74	(0.29)
Mighty-Mite Molded Mortar	n/a	n/a	0.66[b]	(0.26)
Commercial Pipe - SDR = 21[a]	0.54	(0.21)	0.58	(0.23)

[a] SDR stands for Standard Dimensional Ratio and equals the pipe outside diameter divided by the minimum wall thickness.

[b] Mighty-Mite Mortars have a wall that varies in thickness, grading from thickest at the bottom to thinnest at the top. The value reported is for 8.9 cm (3.5 in) above the bottom.

[c] Manufacturers tend to extrude HDPE pipe with walls that exceed the minimum specified thickness. The thickness reported here are those measured on the mortars used in this and future studies.

Equation 1 also identifies burst strength as proportional to the tensile strength of the pipe material. High Density Polyethylene resin type PE-3408 has the highest rated tensile strength commonly available. Thus this is the resin type of choice, and the one used for mortars in this study.

The use of HDPE for fireworks mortars pressure-stresses the pipe in a substantially different manner than typical plumbing applications. Probably the most significant difference is the very short duration of the pressure generated by shell firings, typically less than about 0.03 seconds [9,10]. This is less than one 10-billionth the time of a typical plumbing application. The resiliency of HDPE, coupled with the very brief interval of the pressure pulse from shell firings, seems to provide it with significantly greater strength than would be predicted from Equation 1 [10].

HDPE is a thermoplastic i.e., it melts at high temperature; thus its strength diminishes as temperature rises. The temperature rating factor for HDPE pipe is its relative strength as a function of temperature in typical plumbing applications. Figure 1 illustrates the effect of temperature on the burst strength of HDPE pipe [11]. As can be seen, the strength factor has been normalized to 1.0 at 23.9°C (75°F), and it falls by 10% for every 7.2°C (13°F) rise in temperature. Figure

1 is greatly simplified and not a completely accurate representation of the manner in which HDPE pipe loses strength with increasing temperature. Nonetheless, it clearly suggests that the strength of HDPE mortars must fall to dangerously low levels as their temperature rises. With each shell fired, the mortar a absorbs portion of the thermal energy released from the burning black powder; this manifests itself as a rise in the temperature of the mortar. Thus, unless the mortar is allowed to cool between repeated shell firings, the mortar will lose strength with each firing, as its temperature rises.

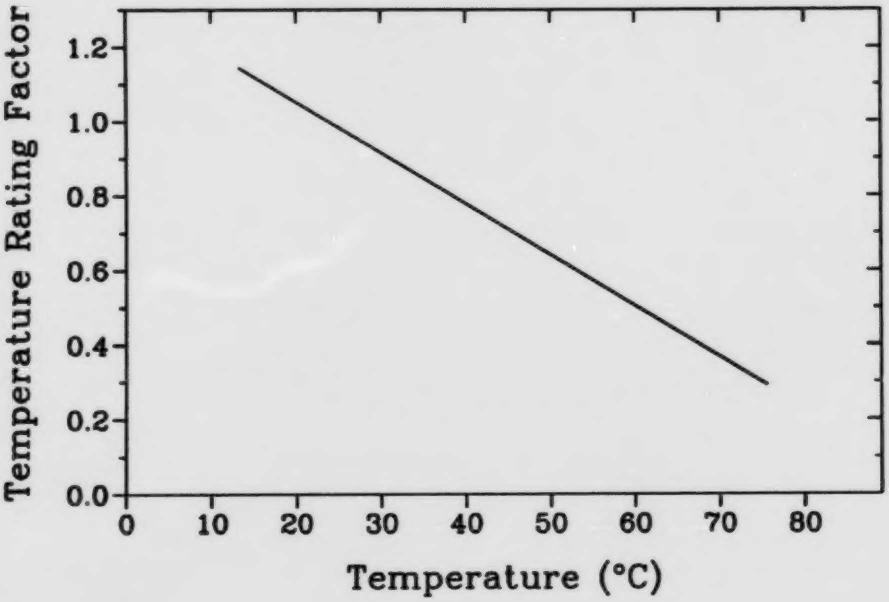

Figure 1. Temperature rating factor for HDPE pipe, derived from Reference 11.

EXPERIMENTAL METHOD

The first portion of this study was conducted to learn how measurements should be made. One piece of information needed was, how long after thermal energy (heat) is deposited on the inside of a mortar does it become evenly distributed throughout the wall of the mortar? This information was needed to design intelligent shell firing and temperature measuring sequences. Another piece of information needed was, at what point on the mortar does the highest temperature occur? This is the point where the mortar is most likely to fail and where the temperature needs to be monitored most closely. Finally, in preparation for destructive testing, what method should be used to raise the temperature of the mortars to near their failure temperature?

In the second portion of this study, the basic data needed to help establish the safe limits for repeat firing was collected. This consisted of determining: how much thermal energy is deposited in the mortar with each shell firing; what is the rate of heat loss from the mortar as a function of mortar temperature and its environment, and what is the mortar temperature at which failures could be expected to occur for typical spherical and cylindrical shells.

Finally, based on the data collected, rough guidance was offered for safe limits of repeat firing of 10.2 cm (4 in), SDR-17, HDPE mortars.

TESTS AND MEASUREMENTS

THERMAL EQUILIBRATION TIME

When an aerial shell is first fired from a mortar, the inside of the mortar is very hot and the outside has not begun to warm-up. As time passes, heat energy is distributed more evenly throughout the wall. Eventually, if essentially no energy is lost from either the inside or the outside of the mortar, the temperature will be the same at every point in the wall. The first measurement in this study was of the time required to distribute the thermal pulse from a shell firing throughout the wall of the mortar. This was needed to establish the appropriate time delay after shell firings before other measurements could reliably be made. It was also needed to design the shell firing sequences for some of the tests that would follow.

For an HDPE mortar, the time it takes to reach thermal equilibrium is a function of wall thickness, with thicker walls requiring longer times to equilibrate. Thus, the thickest-walled mortar (commercial pipe with SDR-17) was examined first. For this determination, a single thermocouple was attached to the exterior of the mortar, a few centimeters above its mortar plug. The thermocouple was attached with a narrow strip of PVC tape. Then the mortar was loosely wrapped with fiberglass insulation and mounted in an enclosure to hold the mortar and prevent drafts from affecting the measurement. At this point, the mortar was ready for a series of test firings. After each firing, a plug was inserted into the mouth of the mortar to reduce thermal loss (from convection) from inside the mortar. Each measurement consisted of monitoring the temperature rise of the exterior of the mortar as a function of time. The data from a series of tests are shown in Figure 2 as the percent of maximum temperature reached.

As can be seen, the maximum temperature is reached in about two minutes and certainly within three minutes. At that time, it is assumed that the mortar has reached essentially a constant temperature throughout the thickness of the wall. In the data reported below, if a time after firing is not given for a temperature measurement, that time is approximately three minutes.

DISTRIBUTION OF THERMAL ENERGY ALONG THE LENGTH OF A MORTAR

All else being equal, the most likely point of failure for an over-heated HDPE mortar will be where it is hottest. Thus it is important to examine the distribution of temperature along the length of a mortar to determine where the temperature is highest.

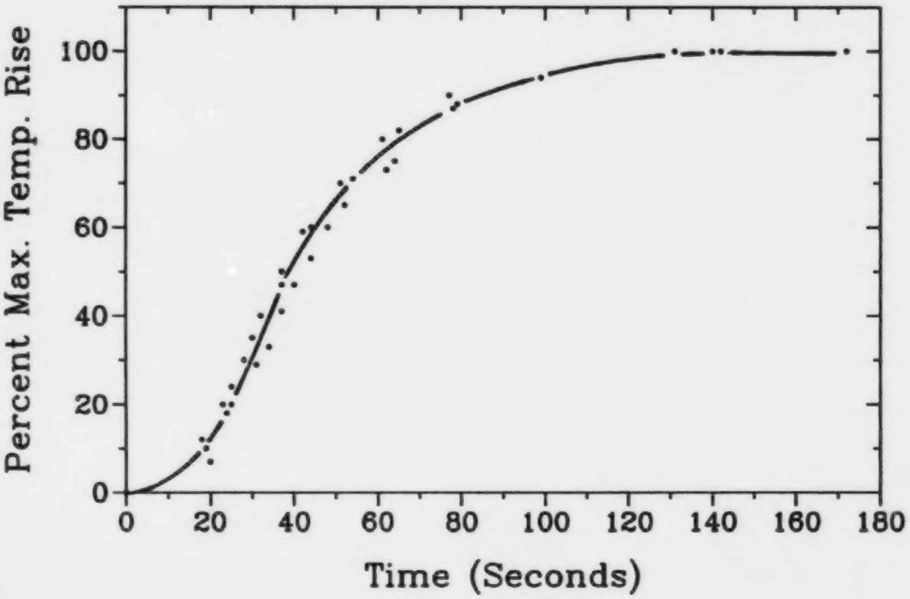

Figure 2. HDPE mortar warm-up curve from test firings of aerial shells.

For this determination, a series of six thermocouples were attached along the length of the test mortar (SDR-17). Attachment points were at 0.0, 2.5, 7.6, 15.2, 27.9, and 45.7 cm (0, 1, 3, 6, 11, and 18 in) above the mortar plug, which was made of 3.8 cm (1.5 in) thick wood. Thermocouple attachment was again made using narrow strips of PVC tape. Then the mortar was loosely wrapped with fiberglass insulation and mounted in an enclosure to hold the mortar and prevent drafts from affecting the measurements. At this point, the mortar was ready for a series of test firings. After each firing, a plug was inserted into the mouth of the mortar to reduce thermal energy loss. Each measurement consisted of recording the exterior temperature of the mortar approximately three minutes after the test firing.

Both spherical and cylindrical test shells were used. Spherical shells were tested with and without a lift cup, to raise the shell above the bottom of the mortar; also, both 2F-A and 4F-A black powder were used for lifting spherical shells. Table 2 lists the various shell and lift configurations used.

Test results are summarized in Figures 3, 4 and 5, where each data point is the average result from at least three test shell firings. Figure 3 presents the mortar temperature profiles for spherical shells fired without a lift cup (dead volume = 345 cm^3) when using 4F-A and 2F-A black powder. Figure 4 presents the results for spherical shells with lift cups (dead volume = 559 cm^3), and Figure 5 presents the results for cylindrical shells.

Table 2. Test Shell Configurations Used in Determining Mortar Temperature Profiles.

Shell					Lift			Dead Volume	
	Mass		Diameter			Mass		[a]	
Type	g	(oz)	cm	(in)	Type	g	(oz)	cm^3	(in^3)
Sph	363	(12.8)	9.4	3.7	2F-A	28	(1)	345	(21.6)
Sph	363	(12.8)	9.4	3.7	4F-A	28	(1)	559	(34.1)
Sph	363	(12.8)	9.4	3.7	2F-A	28	(1)	345	(21.6)
Sph	363	(12.8)	9.4	3.7	4F-A	28	(1)	559	(34.1)
Cyl	500	(17.6)	9.2	3.6	2F-A	55	(2)	257	(15.7)

[a] Dead volume is the space below an aerial shell when resting in a mortar. Dead volume affects the maximum mortar pressure and the distance above the bottom of the mortar where maximum mortar pressure is reached. For more information about pressure profiles and the effect of dead volume, see References 9 and 12.

The curves in Figures 3, 4 and 5 should only be considered approximations of actual mortar temperature profiles. This is because only a limited number of tests were averaged together and only a limited number of thermocouples were used near the bottom of the mortar where the profile is rapidly changing. Nonetheless, the curves are quite consistent and appear essentially as expected. For example:

1. Mortar temperature slowly increases as one proceeds along the length of the mortar toward the bottom. Presumably this is because as one moves down the length of the mortar, it has been exposed to the high pressure lift gases for longer periods of time. (The amount of thermal energy transferred to the mortar is a function of both the temperature and the pressure of the lift gases, and the length of that exposure.)
2. The mortar temperature suddenly decreases just before reaching the plug. Presumably this is because some of the heat initially deposited there has been conducted away. (The test mortar was closed on the bottom with a wooden plug, which, along with the mortar wall below the top of the plug, constitutes a heat sink.)
3. The distance above the plug to where maximum temperature occurs is roughly proportional to dead volume. Presumably this is because as dead volume increases more of the mortar just above the plug receives the maximum exposure to the hot lift gases, with the effect that the point of greatest average exposure moves upward.

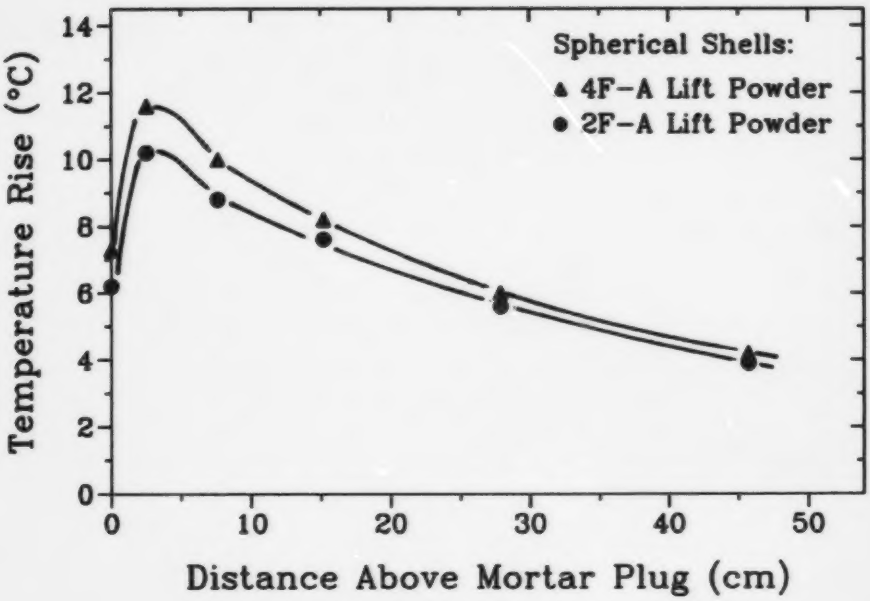

Figure 3. Average mortar temperature profiles for spherical test shells without lift cups.

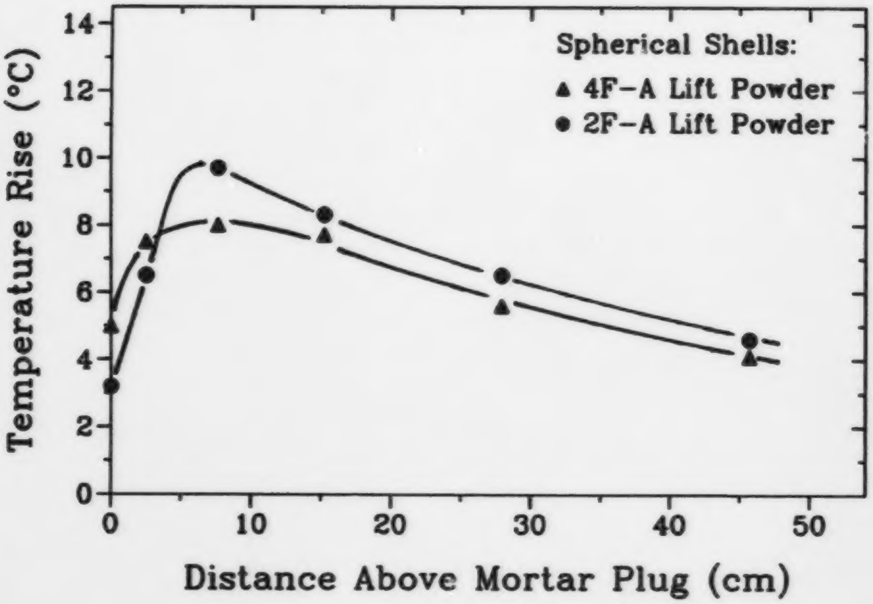

Figure 4. Average mortar temperature profiles for spherical test shells with lift cups.

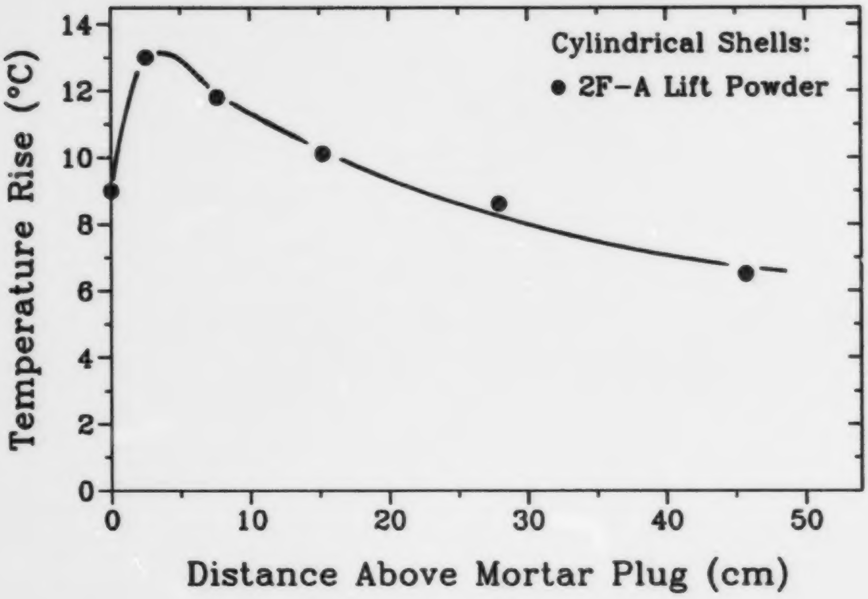

Figure 5. Average mortar temperature profile for cylindrical test shells.

4. The maximum temperature detected is greatest for cylindrical shells, followed by spherical shells without a lift cup, and is least for spherical shells with a lift cup. Presumably this corresponds to the relationship for expected mortar pressures for those types of shells. (The amount of thermal energy transferred to the mortar is a function of the pressure of lift gases.)

In the following results, a point 5.1 cm (2 in) above the mortar plug was chosen for measurement of maximum mortar temperature.

METHOD FOR PRE-HEATING THE TEST MORTARS

It might seem that the best way to heat HDPE mortars to near their failure temperature, in preparation for determining the conditions resulting in their failure, would be to repeatedly fire shells from them. One obvious problem with this is the expense of preparing the large number of test shells, which would be considerable. However, there are other technical and operational problems. For example, the amount of thermal energy deposited in the mortar during test firings of identical shells seems to vary significantly from shot to shot. Figure 6 presents the results from six test firings of spherical shells with lift cups and using 4F-A lift powder. The temperature rise for each thermocouple is shown for each test. The gridded area illustrates the range of values observed.

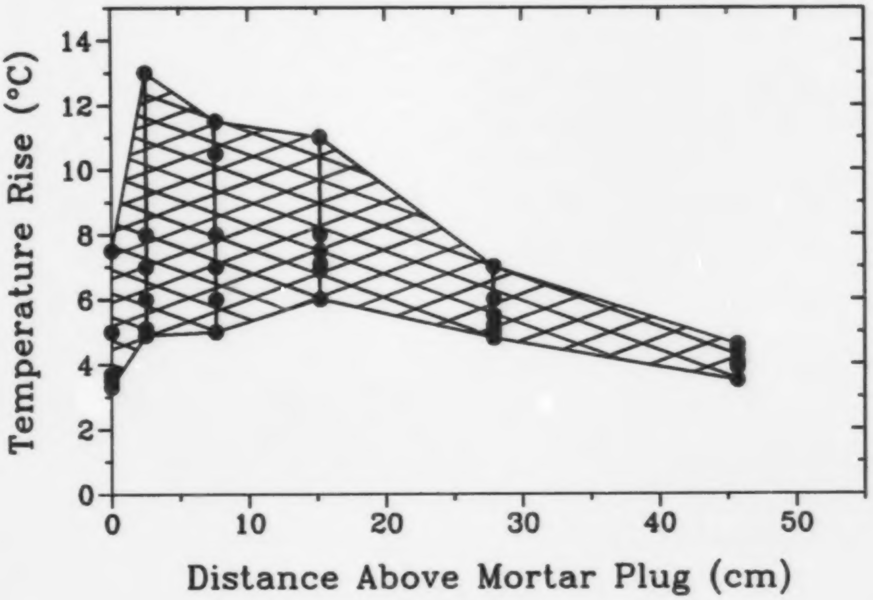

Figure 6. Range of mortar temperature values observed during test shell firings. [Spherical shells with 4F-A lift powder and with lift cups.]

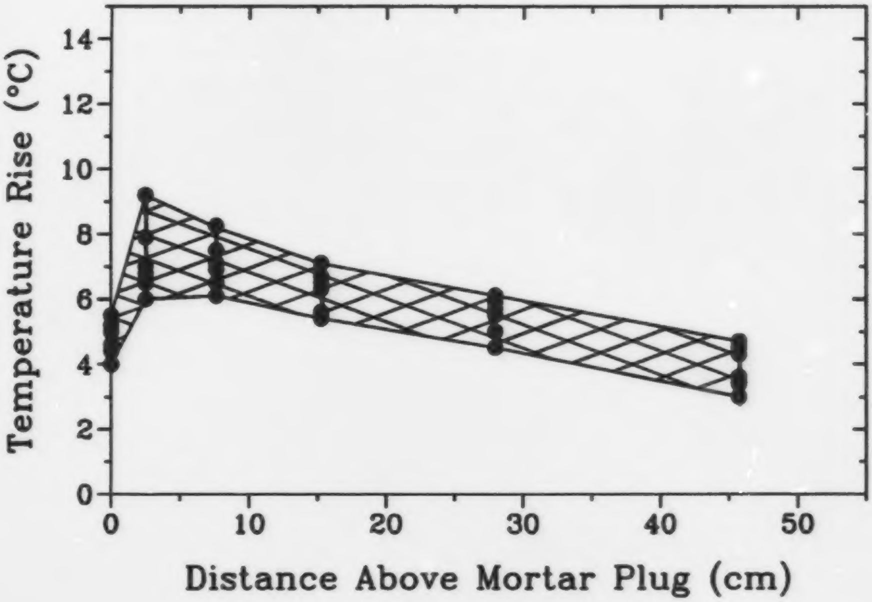

Figure 7. Range of mortar values observed during test burning of bags of lift powder alone [28 g (1 oz) of 4F-A lift powder].

At present, the authors do not fully understand the reason for the range of measured temperatures in the above tests. However, it is likely that it is related to the dynamics of the gas flow in the mortar during its firing. It is possible that much of the variability is merely an artifact caused by only measuring temperature at a series of points along one side of the mortar. The authors speculate that when a shell is propelled up the mortar, it moves somewhat from side to side, within the constraint imposed by the walls of the mortar. As it follows this zigzag path, the gap between the shell and mortar varies from place to place and moment to moment. As a result, the amount of high temperature lift gas escaping between the shell and the wall varies in similar fashion. If this is the case, then it is likely that the amount of thermal energy received by the mortar wall at various points depends on the details of the shell's motion within the mortar, which will be different for each shell firing. Thus if measurements are made along a line of points up one side of the mortar, it seems likely that significant variations from shot to shot could be expected.

Partially as a test of the above hypothesis, but primarily to find a more predictable method of heating mortars, another series of measurements were made. In these tests, bags of lift powder, without attached test shells, were placed in the test mortar and fired. The results from these tests are shown in Figure 7 On average there was slightly less thermal energy transferred to the mortar, but the most striking difference is that the values for the points are more closely grouped. For this reason, plus the cost savings from firing only lift powder and not test shells, it was decided to pre-heat test mortars by repeatedly burning bags of lift powder in them. So-called B-blasting powder (sodium nitrate oxidizer) is slower burning and was found to produce greater mortar temperature increases than normal A-blasting powder (potassium nitrate oxidizer). The average temperature rise for 28 g (1 oz) of 4F-A powder is about 7°C (13°F), while that for 1F-B powder is about 37°C (66°F). Thus B-blasting powder was chosen to preheat the test mortars.

AMOUNT OF THERMAL ENERGY DEPOSITED IN MORTAR DURING SHELL FIRING.

The data needed for this determination, is the same as already reported to establish the mortar temperature profiles shown in Figures 3, 4 and 5. Knowing the temperature rise of an object, its mass, and its heat capacity (specific heat), it is a simple matter to calculate the amount of heat (thermal energy) absorbed, see Equation 2.

Eq. 2. $q = m \cdot C \cdot \Delta T$ where,

q is the heat transferred in calories,

m is the mass of the object in grams,

C is the heat capacity in cal/g°C (0.50 cal/g°C for HDPE [13]), and

ΔT is the change in temperature in °C.

Considering a 1 cm^2 section of a SDR-17 mortar, with a typical wall thickness of 0.74 cm [Table 1], and given that the density of HDPE averages 0.95 g/cm^3[13], the heat required for a 1°C (1.8°F) temperature rise is 0.35 calories. The maximum temperature rise seen in the various profiles shown in Figures 3, 4, and 5, averages about 10°C (18°F) for spherical shells and about 13°C (23°F) for cylindrical shells. The thermal energy deposited in the mortar at the point of maximum temperature rise is approximately 3.5 and 4.5 cal/cm^2 for spherical and cylindrical shells, respectively.

As an aside, it was felt that it might be of interest to determine the fraction of thermal energy, whih is produced by burning the black powder lift that is absorbed by the mortar. This was calculated by mathematically dividing the mortar into six sections of varying length, one section centered on each thermocouple. Then, assuming the temperature rise of each section was that observed by the thermocouple, Equation 2 was used to calculate the heat deposited in that section. The total thermal energy absorbed was determined by summing the individual values. This resulted in estimates that, typically, the mortar absorbs 1.2 and 1.6 kcal of energy when firing spherical and cylindrical shells, respectively. Knowing the amount of lift powder used, and that the heat of reaction for black powder is 0.66 kcal/g [14], the total heat produced was calculated. This amounts to about 18 and 36 kcal for spherical and cylindrical shell firings, respectively. Thus the mortar absorbs approximately 6.7 and 4.4 percent of the total thermal energy produced by the lift powder during the firing of spherical and cylindrical shells, respectively.

RATE OF THERMAL ENERGY LOSS FROM MORTARS

Thermal energy always migrates from hotter to cooler areas, and the rate of heat transfer is a function of the temperature difference (temperature gradient) between the two areas. Thus in the examination of the heat loss from mortars, the rate of loss was always considered in terms of temperature gradients, and not specifically in terms of mortar and environment temperatures. This provides solutions that are more generally applicable, instead of requiring data for each different mortar and environment temperature.

There are three mechanisms for transferring thermal energy: radiation, convection, and conduction. For above ground mortars, only convection is significant; the hot mortar is in contact with cool air, which acquires heat from the mortar and then drifts away. For buried mortars, only conduction is significant; the hot mortar is in contact with the cool ground, which acquires heat from the mortar and passes it from layer to layer through the ground. Heat transfer problems are often fairly simple to solve analytically, however, in this case there are complexities that make an analytic solution impractical and possibly unreliable as well. Thus an empirical approach has been taken. For this, mortars were instrumented with thermocouples at six locations, attached in the manner described above. However, for above ground mortars, a rubber band was placed around the mortar and over the thermocouple to augment its attachment. This was necessary because, at the temperatures during testing, the adhesive on the tape failed to provide sufficient attachment strength. The test mortar was then placed in the environment to be studied.

To study above ground mortars, a stake was used for mortar support. The mortar was attached to the stake so as not to interfere with or distort the temperature measurements. Shields were erected around the test mortar to shade the mortar from direct sunlight and breezes. However, the shields were not close enough to restrict free air circulation around the mortar. At this stage of work, no attempt was made to account for effects that would be produced by having mortars in racks. (Racks would restrict air circulation to some extent, insulate some spots on the mortar, and may place heated mortars close to one another.)

To study buried mortars, a wooden box was used to support the mortar. The box provided about 16 cm (6.5 in) of space around the mortar; the space was filled with dry sand. (Hopefully, data will eventually be collected using wet sand, which will have greater thermal conductivity and a higher heat capacity.)

To begin the process of taking measurements, the mortars were heated by burning packets of black powder in them. The packets were small enough and their burning separated enough in time so as not to damage the mortar by localized over-heating. Generally, 28 g (1 oz) packets of 1F-B powder were used, with two minutes elapsing between burnings. Figure 8 is an example of the temperature history recorded by thermocouple number two (TC2) in one above ground thermal energy loss experiment.

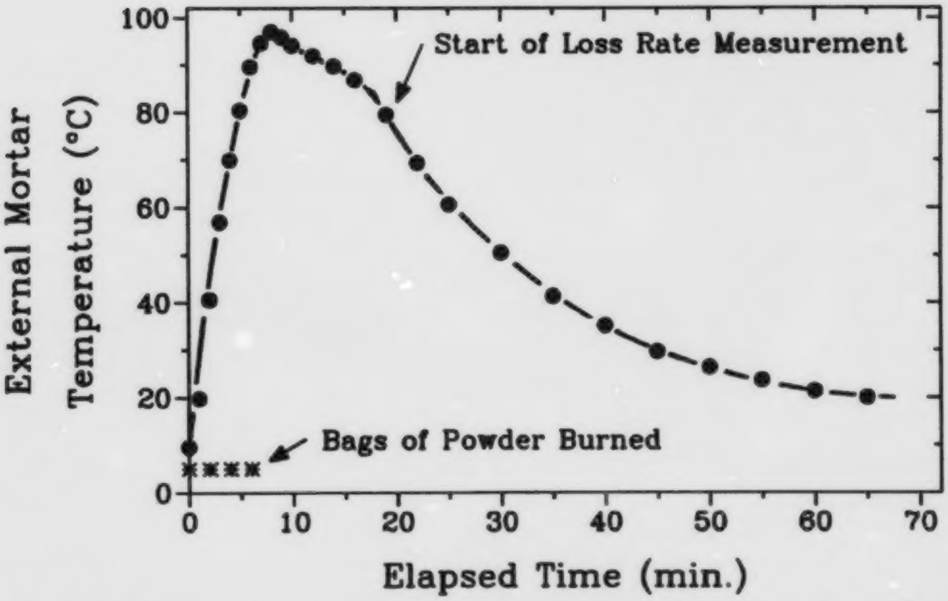

Figure 8. Temperature history recorded by TC2 and TC3 for an above ground HDPE mortar.

It is at the approximate location of TC2 and TC3 where the mortar is hottest and is expected to fail during use. Thus this is where attention was focused. Figure 9 presents the results from one of three above ground tests. Here, temperature gradient is the difference between mortar exterior and air temperatures. The rate of heat loss is reported as temperature loss rate because the two are proportional (see Equation 2) and because this information will be of more direct use later in this report.

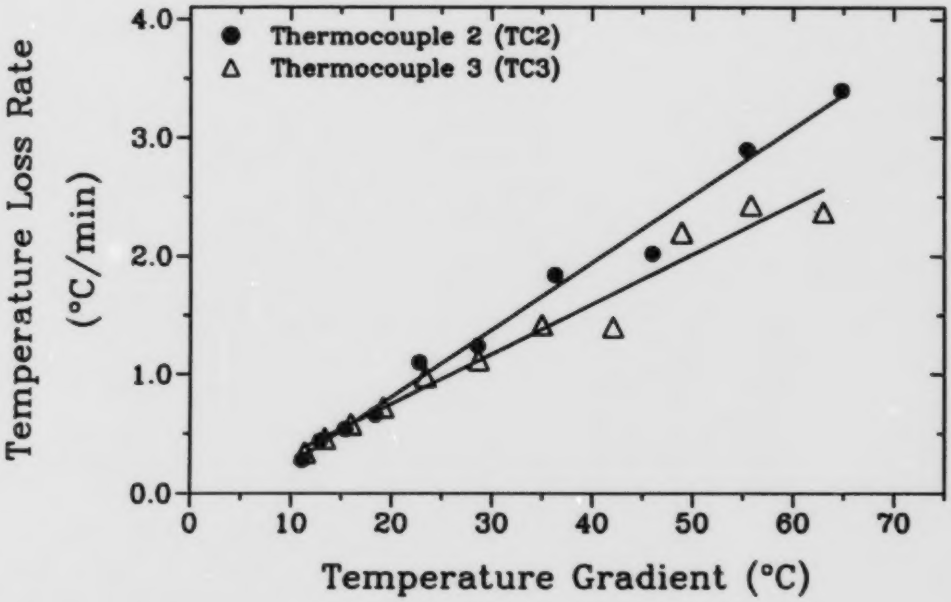

Figure 9. Temperature loss rate at TC2 and TC3 for an above ground HDPE mortar.

It appears that the temperature loss rate at TC2 and TC3 is a linear function of temperature gradient. Also the loss rates at TC2 and TC3 are similar, but not precisely the same. Considering that the mechanism for heat loss is convection, it is not surprising there is a difference and that the rate of heat loss at TC3 is less than at TC2. The heat being convected away from near TC2 would be expected to raise the air temperature over TC3 higher than ambient air temperature, thus reducing the efficiency of heat loss at that point.

Of necessity, the rate of temperature loss (heat loss) must be zero when the temperature gradient is zero. However, the Y-intercept for the lines in Figure 9 are about -0.3°C/min. It is believed that this is an artifact of fitting the data to a linear relationship and not including data for near zero temperature gradients. Nonetheless, in the temperature gradient range of greatest interest, this should be of no concern.

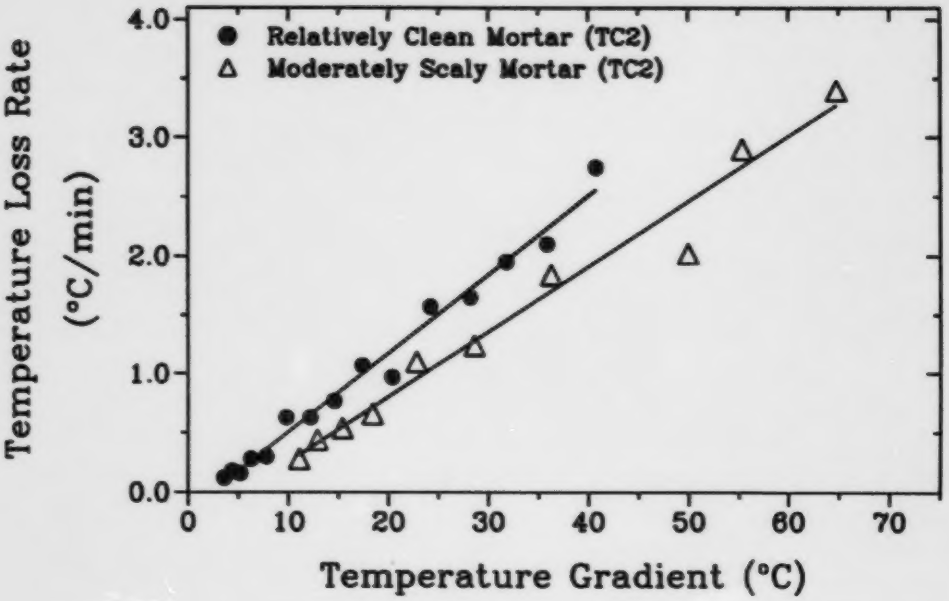

Figure 10. Temperature loss rate as a function of cleanliness of an above ground mortar.

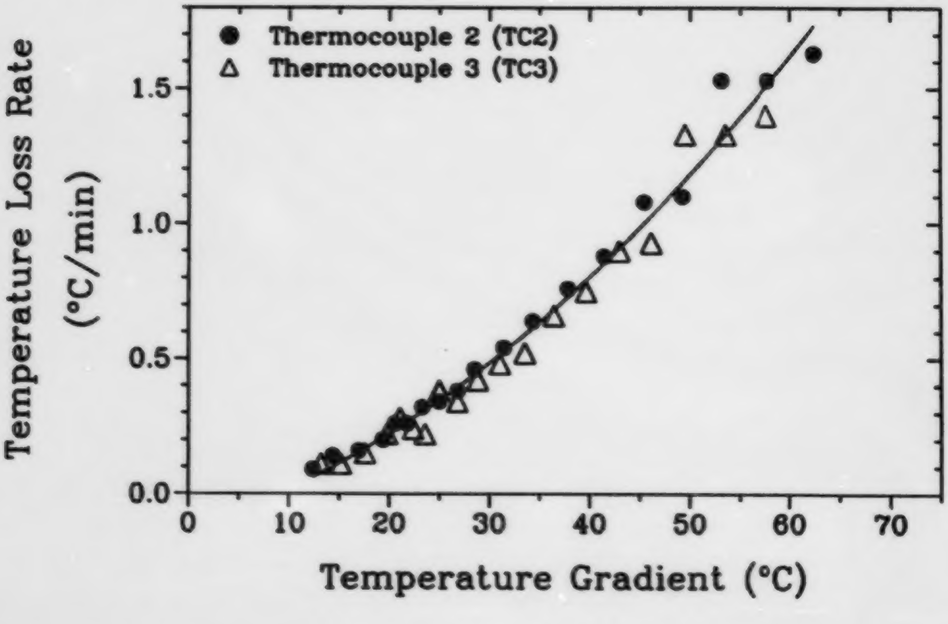

Figure 11. Temperature loss rate at TC2 and TC3 for a buried mortar.

When Figure 9 results were compared with those of earlier experiments, it was observed that the temperature loss rate had fallen about 20 percent for the same mortar (see Figure 10). Upon examination of the mortar, apparently a scale of combustion products had built up on the interior mortar walls. While the direction of the change is what would be expected, its magnitude is larger than would have been expected. Thus, in predicting the safe limits for repeat firing, it seems that the cleanliness of the HDPE mortar also must be considered. The temperature loss rate for a clean mortar, shown in Figure 10, is:

Eq. 3 $$\text{Temperature Loss Rate (°C/min)} = 6.7\text{x}10^{2}(\text{Gradient}) - 0.16$$

For a buried mortar, the rate of heat loss was observed to be almost exactly the same for both TC2 and TC3, see Figure 11. When compared with above ground mortars, the most significant difference is that the temperature loss rate is only about one-third as much for the same gradient. Also different is that the relationship is not linear, the curve is very nearly a parabola and the temperature loss rate is given in Equation 4.

Eq. 4 $$\text{Temperature Loss Rate (°C/min)} = 5.0\text{x}10^{-4}(\text{Gradient})^{2}$$

With above ground mortars, because even minor air currents continually carry heated air away, the ability of the air to absorb thermal energy does not diminish with time. However, this is not the case for buried mortars, where the ground nearest the mortars tends to become saturated with heat. To examine this effect, a series of three thermal energy loss experiments were conducted, one immediately following the other, see Figure 12. Using this data, three loss rate curves were derived illustrating that the ability of the ground to absorb heat diminishes with each cycle, see Figure 13. This is an effect that must be considered when attempting to define limits for repeat firing of buried HDPE mortars.

FAILURE TEMPERATURE OF HDPE MORTARS

For these measurements, two mortar configurations were used. In some tests, the mortar was insulated, essentially reducing the rate of heat loss to zero. This represents the extreme case of completely thermal-saturated ground. In other tests, the mortars were not insulated and were exposed to cool, 0°C - 20°C (30°F - 70°F), air. In these tests, the mortars were preheated to near their expected failure temperatures; then aerial shells were fired to test whether the strength of the mortars had remained high enough to survive. Mortars that survived were heated to still higher temperatures and tested again. This process was continued until each mortar had failed. Because the firing of cylindrical shells pressure-stresses mortars more than spherical shells, information was collected for both types of shells. In this way, data was collected identifying the highest mortar temperature for which mortars survived and the temperatures at which they failed. Result from those experiments are listed in Table 3.

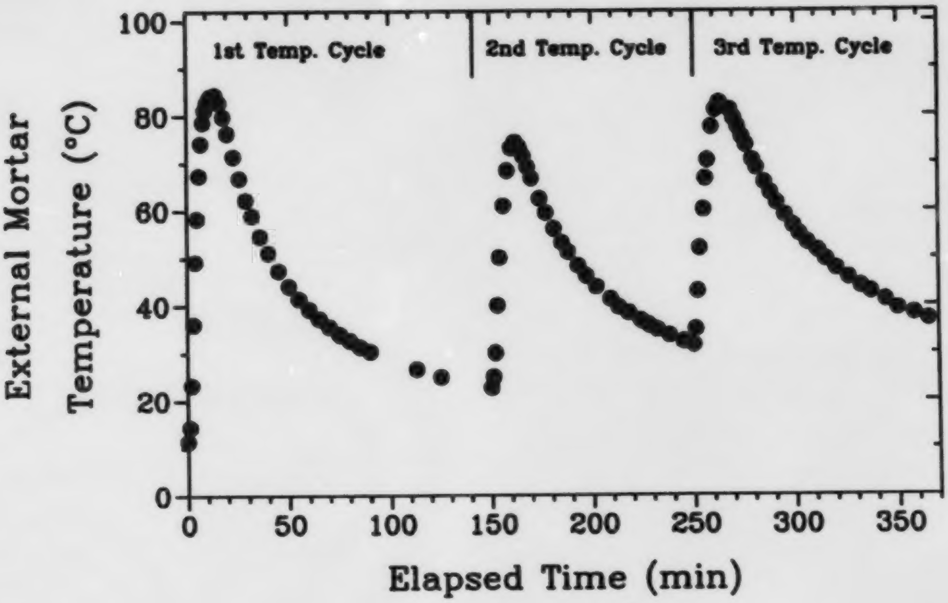

Figure 12. Three consecutive temperature loss rate experiments for a buried mortar.

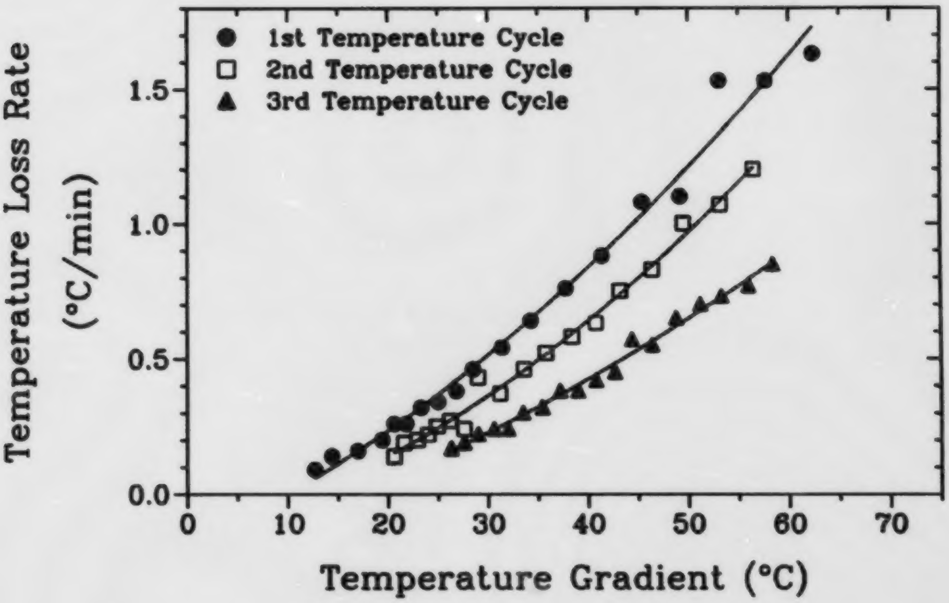

Figure 13. Temperature loss rate at TC2 and TC3 for a buried mortar illustrating the effect of thermal saturation.

Table 3. Survival and Failure Temperatures for 10.2 cm (4 in), SDR-17, HDPE Mortars.

	Maximum Temperature Survived		Temperature Where Mortar Bulged or Burst	
Shell Type	°C	(°F)	°C	(°F)
Spherical	88	(190)	86 [b]	(187)
	99	(210)	88 [b]	(190)
	92	(198)	97	(207)
	102 [a]	(216)	96	(205)
			97	(207)
			108 [a]	(226)
Cylindrical	96	(205)	76 [b]	(169)
	88	(190)	90	(194)
			103 [a]	(217)

[a] The mortar was wrapped in insulation for the test.

[b] The mortar only bulged; it did not burst.

During the tests reported in Table 3, in at least one case, a mortar had visibly bulged, ≈0.3 cm (0.12 in), during preheating. Recall that no significant pressure is produced when bags of black powder are burned in the mortars. Thus, the bulging in that one case cannot be attributed to the high pressure of shell firing. In other tests, after the mortars had bulged slightly, they continued to fire shells successfully even though the temperature had been raised significantly. For example, the mortar that bulged at 76°C (169°F), while firing a cylindrical shell, continued to withstand cylindrical shell firings at 88°C and 92°C. The bulges were small both in terms of change in diameter [≈0.3 cm (0.12 in)] and mortar length affected [≈5 cm (2 in)]. Accordingly, it seems likely that the mortar pressure during subsequent shell firings was about the same as for unbulged mortars. Thus the survival of the mortar during subsequent firings at higher temperatures, probably cannot be attributed to those firings putting significantly less stress on the mortars. At present, the authors do not fully understand the bulging phenomenon.

It might be of interest to note that on average the mortar burst points were 2.9 cm (1.1 in) above the plug and ranged from 2.2 to 5.5 cm (0.9 to 2.0 in) above the plug. Based on the estimated point of highest mortar temperature, temperatures reported in Table 3 were recorded at about 5 cm (2 in) above the mortar plug. The location of the burst points, which corresponds to the point of highest mortar temperature, suggests that a point slightly closer to the plug should be used in future tests.

The overall strength of an HDPE mortar at high temperature depends on the temperature of the pipe throughout the thickness of its wall. As an example of the complexity this introduces, consider the case where the mortar is exposed to relatively cool air on its exterior. In this case, the temperature measured on its exterior wall is a complex function of both the temperature of the mortar, the air temperature, and the degree to which the air is in motion or is stagnant. The data for non-insulated mortars in Table 3 do not consider this complication, and thus must be considered only as a general guide. Based on the work performed to date for 10.2 cm (4 in), SDR-17, HDPE mortars exposed to relatively cool and calm air, it seems that the maximum service temperature (as measured on their exterior) is not more than about 75°C (167°F) for typical cylindrical shells and about 85°C (185°F) for typical spherical shells. For insulated mortars, with near zero heat loss, these temperatures are probably about 15°C (27°F) higher. For mortars in dry sand (roughly equivalent to dry soil) the rate of heat loss should be somewhere between that for cool air exposed mortars and insulated mortars. Thus, it seems that the maximum service temperature of buried mortars, as measured on their exteriors, would be no more than about 80°C (176°F) for typical cylindrical shells and 90°C (194°F) for typical spherical shells.

PRELIMINARY RESULTS

The authors feel that the results generated to date are only barely sufficient to suggest even the most preliminary guidelines for repeat firing of 10.2 cm (4 in), SDR-17, HDPE mortars with wooden plugs. It is only because this subject is of considerable interest to some and has important safety ramifications, that an attempt was made to offer any guidance at this time.

During repeat firing of HDPE mortars, some amount of heat will be lost from the mortar between firings. Therefore a worst case scenario would be the case of a well insulated mortar when no heat loss occurred. Thus, if it is determined how many shells of a given type can be successfully fired from an insulated mortar, then surely at least the same number could be successfully fired during a fireworks display. If it is assumed that:

— the initial temperature of the mortar is 20°C (68°F);

— only spherical shells of typical weight and normal lift charges are fired,

— the maximum mortar temperature rise produced by these shells is 10°C (18°F) per firing;

— the maximum temperature rise for such shells before mortar damage occurs is 100°C (212°F) [insulated mortar results]; and

— the thermal energy lost during the process of shell firing, from a non-insulated mortar, provides a sufficient safety margin;

= then it could be concluded that eight typical spherical shells could be rapidly fired from the same mortar without it failing.

If a greater safety margin were felt appropriate, the number of shells could be reduced to seven. For each 10°C (18°F) increase in initial mortar temperature, the number of shells should be reduced by one, and conversely, could be increased by one for each 10°C (18°F) decrease in initial mortar temperature. Following similar logic, and for similar conditions for cylindrical shells, it could be suggested that as many as five typical cylindrical shells could be safely fired in rapid succession.

Having once raised an HDPE mortar to its limiting service temperature, the question might then be how long to wait between subsequent firings. For above ground mortars, if it assumed that:

- — air temperature is 20°C (68°F);
- — air flow around the base of the mortar is not obstructed;
- — adjacent mortars are not hot enough or close enough to affect the mortar of interest;
- — the interior of the mortar is fairly free of scale; and
- — during repeat firing, because of heat loss during the process, the exterior temperature of the mortar had risen to approximately 70°C (158°F), producing a temperature loss rate of a little more than 3°C (36°F) per minute;

═ then subsequent shells could be fired every three or four minutes.

Following similar logic, and for similar conditions for cylindrical shells, it could be suggested that subsequent cylindrical shells could be fired every four or five minutes.

For buried mortars, the rate of heat loss for the same temperature gradient is about one-third that for above ground mortars. Accordingly, the time between subsequent firings should then be about three-times as long as that for unobstructed above ground mortars with the same temperature gradient.

ACKNOWLEDGEMENTS

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FIREWORKS PRINCIPLES AND PRACTICE: THIRTY YEARS

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People used to say, Why don't you write a book about fireworks? We all think that it might be a nice idea to write a book but you have to ask the question; 'WHY.' I certainly did not have any ambition to try and teach other people how to make fireworks and although I had a very academic approach to the subject in those days, it was obvious that friends in commerce would not thank me for disseminating information. The basic question thus is to ask where you draw the line between an academic interest in a subject where the enthusiastic amateur wants to find out every bit of available knowledge on the one hand, and on the other trying to run a business and keep ahead of your commercial rivals.

Up to 1980 I have to confess that my interest was academic. My wife says that my life is consumed with fireworks. She says that I eat, sleep fireworks and take them to bed with me. Like the real enthusiast I am always happy to talk to people about fireworks and to hear what their experiences have been. You can always learn from other people too and it does not matter how old you are you can learn something. I spent much of my life as a schoolmaster and as I always used to say, if you don't know everything when you are eighteen, then you never will.

However there is a danger and invariably it involves money. If you earn your living making fireworks and selling them, everything boils down to commercial viability. It may not be a case of whether you know how to make a good violet shell but how cheaply you can make it. It is not so much the composition as the technique. It may well be that huge sums of money have been spent on some seemingly straightforward production technique, but the amateur seems to think that he can just go along and ask for the information on a plate.

I understand this problem, because I have been through it. I have friends who have said it to my face as well as behind my back. However now that I have commercial interests and a good deal of my personal capital in a business it is very clear, but I also have to make excuses for the amateurs. They have a blind spot. They are so interested and in love with their subject they want to know everything about it. Quite a lot of people in the industry are not in love with fireworks at all, their interests are elsewhere perhaps it is money. I feel that I have to say this because I have a foot in both camps so to speak. Actually there is also another group who play a part in the firework trade and I shall return to this later. This group consists of civil servants and researchers some of whom are neither interested in fireworks nor commerce. It may well be that they are only interested in their own bureaucratic or even idiosyncratic world but they can have an effect on commerce with serious consequences.

So how did Fireworks Principles and Practice come into being? The answer is by accident. Like most of us I had a copy of Weingart's Pyrotechnics and I felt that the time had come when it should have been re-written. I had already met Dr Herbert Ellern and made a contribution to his book and so I wrote to Chemical Publishing to ask if they would like me to make a revision of Weingart. The reply came back that they would prefer a new book. It was as simple as that.

Simple is not the appropriate word however. I would describe the writing of a practical book as a 'Knife edge'. The dilemma was to find a way of writing something that was accurate and practical without giving offence to friends in commerce who had over the years been kind enough to pass on much of their interest and experience. By and large I feel that this was achieved quite well and in its day it was a stage in the field of writing about fireworks. Looking back, I might have done things somewhat differently and if I had known then what I know now I might have submitted the work for a higher degree.

By the late 60's I had the good fortune to be in contact with Dr Takeo Shimizu and so it was natural to ask him to join in the writing of the book in the same way as I had done for Dr Ellern. We had all been fascinated by the way that things had developed in Japan between the two World wars but our detailed knowledge was very scanty and we needed someone with Dr Shimizu's authority to write something which was definitive. I have greatly admired the detailed way in which he has worked and written about our subject, but more than that, the way he has worked to study other languages. There were purists who criticised me for not ghosting the chapter on Japanese fireworks, but in the end I decided that I would leave it largely as he wrote it. I did have to make some changes of course and I know that he will not mind me saying that there was the odd point where the style simply had to be changed; lack of understanding of the finer idiomatic points of language have their funny side, as we all know. Checking for the second edition in 1992 made further minor changes.

A recent review of the 1992 edition of the book in one of the American amateur journals said with typical American candour that there was little to review' and that the book was 'pretty much the same as the first edition.' It then went on to mention a few things that were in fact different. This however misses the point completely. There was no intention to write a new book this time; to do so would not only have changed the character of the work but the attempt to update it would impinge on the work of other people since the first edition. This seems to be symptomatic - if I may say so - of much of what one sees written to-day. Perhaps I could give three examples, titanium, boric acid and HDPE mortars. In the case of the first two, I have every reason to believe, and stand to be corrected, that 1972 was the first time that these materials had been written about but it is interesting to hear the way people speak to-day and where their information came from is of no consequence.

Titanium had always been beyond the pocket of the firework fraternity and basically no one even thought about in an industry which has tended to be very conservative. I am not sure when they started to use it in the aeroplane industry, but the first samples arrived to us in the old firm of James Pain about 1960 and we were very pleased with the results when we used it to replace iron. A quick look at the chemistry made us realise that we would not have any of the corrosion problems which we would expect with magnesium in particular and we knew that it was said to be pyrophoric in very fine sieve sizes only. To this day I have not heard of anyone using it in fireworks commercially before us at that time.

Boric acid is used as a buffer in mixtures which contain nitrates and aluminium is also distinctively English, I suspect. Although it has been used in the UK since 1945 I had never come across it anywhere else. Much research took place in England during the second World War and much of this work has never been published. It may be that some formulations containing barium nitrate and aluminium at that time, were the first to use boric acid as a buffer and that this is possibly where it began. It was certainly a boon to the sparkler manufacturers where the slurry can become very reactive without it and it certainly is useful in mixtures containing sodium oxalate. A yellow glitter star mixture made with sodium oxalate and polished aluminium can become very hot indeed if it is rubbed up in a pestle and mortar with a little water, but boric acid will inhibit this.

This also raises the conservatism of the firework trade. Uncertainty, fear, ignorance, all contribute to the principle that you stick to what you know and do not change anything unless you really must do so. I can think of one or two quite spectacular accidents which have happened through the heating up of compositions containing nitrates and aluminium in the presence of humidity. Talking to people after the accident I asked if they used boric acid, the answer was no, mainly because they had never used it!

The present interest in HDPE mortar firing tubes is another case of this type. People speak about them to-day as if they are quite novel. I think that we started using them about 1968 and find them very useful indeed. We have not yet had a serious problem with them in spite of the fact that we have even managed to burst the odd 75mm salute in them! We are still using pipes which are 20 years old! People who used PVC tubes in the early days had some pretty shattering accidents! Perhaps we were lucky in that the local manufacturer only made pipes of HDPE.

Returning to the use of titanium there are a number of open questions and it is not very clear what has been the cause of some accidents which have taken place when the material is used, and some research has been done with compositions made with it. Most of the evidence seems to suggest that friction is the biggest problem and this is hardly surprising when you consider how hard the material is.

The real reason however for mentioning it in this lecture is to say that I am deeply concerned about research and practice and the way that Government frequently acts, or should I say reacts, to the problem. I do not regard the way that we work with some of our materials as a standard for others and I have to say that I live in fear that the fates may one day conspire to bring all the appropriate conditions together for trouble. I use the word 'fates' deliberately. Deliberately rather than act of God, you can do one or two hazardous things without too much of a problem. You may even include a third factor but it just seems to be that when number four enters at that moment in time that the fates have conspired against you - low humidity, high static, bad housekeeping, ill informed workers, one could go on.

The first titanium that we had available was described as acicular metal fines. The filings were hard, sharp and needlelike, so much so that they invited you to think about the creation of a hot spot between two pieces of this material. Next we got the swarf from the aeroplane industry and although this is a bit softer we did wonder what else may be present. I suspect that some of the UK accidents used this type of material. In time we decided that the granulated sponge titanium seemed to be much the best and this is what we use today and quite apart from anything else it has a much larger surface area.

For the most part we press the material under slow steady hydraulic pressure, incorporate some oil into the mixture, keep the titanium below 20% of the total and preferably much less and we use as little manufactured blackpowder in the mixture as possible. The logic in this is that the press moves slowly and steadily, the oil in the mixture gives some lubrication to the rams and the sides of the tubes. Some people press neat manufactured blackpowder with high percentages of titanium and this seems to me to be tempting fate, ie using the most energetic combination of three ingredients with a very hard metal and heavy pressure. Accidents seem to have happened using a funnel and ram or simply filling fountains with a hammer and drift. People seem to forget that the impulsive force from a hammer is considerable.

It would be wrong to try to make comments about accidents which have happened to others and in any case those of us who have been around for some time know only to well that other factors could be involved. For example it may not have been the titanium mixture at all, it may just be that someone had been using tools contaminated with chlorate for example and purely a case of bad housekeeping. I can think of one or two instances of accidents where I had to wait until the people involved were dead from natural causes before the real truth came out long after the event.

This is where I worry about Government. Government is so often reactive. It is concerned about itself and perhaps its political masters, with the result that things are done which seek to restore the equilibrium. It is very worrying because it is reaching stages where the European industry is being put at severe disadvantages to other parts of the world. Of course things are being manufactured in some places under conditions which are a disgrace. I shall never forget seeing stars being made in a factory with a chlorate/perchlorate composition. The mixture was being mixed in cement mixers and the stars were being pressed with a hydraulic press. As you walked across the room stars crunched under your feet on the concrete floor. To make matters worse the operator was only wearing shorts and sandles in a hot climate and would have suffered very severe burns in a fire. Clearly such conditions should not be tolerated.

But we go to the other extreme in Europe. Government will not be satisfied until everything is filled remotely. It is just a matter of time before we shall all be pressing behind a third of a meter of concrete and it is just a question of whether it is economically viable. If you have not reached the sophistication and cost of charging the composition by machine, you will have to spend time walking around the wall. You can of course have a hole in the wall and 12mm of steel covering during the pressing operation but that means sliding metal moulds along runners. Nor can you easily see what is going on unless you have televisions. The operator may be safer like this, but what other hazards have we created? It is worrying to see whistle composition sliding through holes in the wall.

The same applies to protective clothing. Of course we want to make things better, but we are approaching the point where we are going to be so cocooned and cosmetic that it will be difficult to work. In the UK they used to be obsessed with wearing overshoes to a point of absurdity. Happily things have relaxed and needless to say this is because footwear is not made with nails any more. However in the case of fire, where you need to escape in a hurry, some types of overshoe can be a positive hindrance to quick escape.

Some would argue that there has not been enough research into safety in the past and I am sure that this is true. Perhaps there was not enough funding for a small industry like fireworks and it may well be that greedy manufacturers have not been willing to devote some of their resources to this. The work needs to be done and thank God that some have done so much for the trade, but more work needs to be done in conjunction with the trade. It is one thing to say that you get a fire if you drop a half kilo weight on to some titanium composition from a height of a third of a meter but quite another if it produces an order for remote filling.

You may be forgiven if you get the impression that I am feeling rather down about legislation, but I am afraid that this is the case. Apart from running my business I would like to find time for research. Frankly I do not have the time at all. I have no idea of the exact percentage of my time which is taken up with legislation and bureaucracy but it is at least 25% and it is very expensive indeed. To make matters worse I do not feel that I am getting value for my money because the whole issue is ill-informed and inefficient.

When you consider the legislation that is involved - Health and Safety at Work, British Standard, Classification and Labelling of Explosives, Control of Substances Hazardous to Health, Carriage of Explosives, Control of Explosives, Packaging of Explosives, Training of Drivers of Hazardous Goods, EEC Directives, We can count as many as thirty issues either currently affecting us or about to do so. Is there any wonder that I had anxieties about building a new factory in 1990. It would have been so much easier to give up and import the material from the Far East. This is what happens of course in many cases and I just feel that I have to say that it is an absolute tragedy.

However it is not just the firework industry,it affects many other people as well. For many years I taught chemistry in school and the brutal truth is that we are now brainwashing a whole generation of students into thinking that a good deal of chemistry is more dangerous than it actually is. I fear that it might be even worse in the United States from what I read. Only the other week I read of a school in the USA which alerted all the emergency services because someone had spilt a drop of mercury on the carpet. It is not all that long ago that people took it internally in medicine. I simply cannot resist the temptation to challenge those people who take things to such ridiculous lengths. We have a U.S. Air Force base near to us. They placed our July 4th display at the end of a concrete runway with acres of grass all around us. When they told me that four fire tenders were on hand and asked me if this was sufficient, they took me quite seriously when I asked if they could manage a fifth!

When I started at the old firm of James Pain I went into the mixing shed one day and found the mixer covered in orange arsenic sulphide. I asked him if it had any effect on him and was told that it tended to sharpen his appetite during the weeks that he handled it! He started at the factory when he was 16, worked there all his life and lived beyond his three score and ten. We had some orpiment left and decided two years ago that we would stop using it. Then the problem came to decide what we should do with it since no-one wanted to take it and in the end we just got rid of it by continuing to make fireworks with it. I just wonder where we are going however. Somebody one day is going to start whining about soluble barium and if they decide that we cannot use that in fireworks we shall be in real trouble. The same goes for antimony. It often crosses my mind as I see someone in a restaurant with a burning sparkler on a Baked Alaska.

In a way I see barium in much the same way as the chemists might see chloroform. We now have to manage without Carbon tetrachloride because of the CFC scare just as we can manage without arsenic. To manage without chloroform in chemistry is much the same as trying to make fireworks without barium. They worry about atmospheric levels of solvents and seek to gain a knowledge by stuffing poor rats with chloroform or saccharin until their eyes bulge and they get cancer but I am not sure what it proves. But I hope that you saw the Rumanian doctor from the town where they made carbon black. Everything was black - the children, the houses, the sheep - and the incidence of lung disease was horrific. However the doctor suggested that the incidence of lung cancer was not particular greater than anywhere else. If she was correct in what she said, what a wonderful example. We are not always sensible in the affluent parts of the world, sometimes we are pretty 'dotty'.

In this short talk I have tried - as an old man - to raise a few storm cones. We have a great deal to offer but I am not sure that we are doing ourselves any favours in the way that we are behaving. I would like to draw this to a close by pin pointing three other matters which I feel strongly about.

The first is Blackpowder. It is clear that Sobrero sounded the death knell for gunpowder with his discovery of nitro-glycerine and it was left to Alfred Nobel to exploit it. The real question however is what are we going to do in the future? At one time there were at least fifty sites in the UK manufacturing blackpowder. For more than twenty years we have been buying it from Germany. Only one firm is now left in what was the west of Germany and some of the powder used in Germany is brought in from Jugoslavia. Visiting East Germany some months ago I found that the factory there had manufactured blackpowder but had stopped some twenty years ago. Many of us are aware of the problem, but we do not seem to know what we are going to do about it.

The second is potassium chlorate. We know why the chlorate ion is unstable with an unshared pair of electrons and we should do everything we can to stop people using it for fireworks. We all accept that in some circumstances like smokes or matches there may be no alternative and there are two small uses we have for it in our factory. However by and large it is not necessary and it causes so much trouble. It is particularly annoying to discover the Chinese using it in the braided paper fuse. We had a fire in our factory putting a hog ring around this fuse in the presence of quickmatch and this is the only fire we have had in thirty years! Very often the brutal truth is that potassium chlorate is more easily available and cheaper so people use it, knowing that they should not do so. I feel so strongly about this at a time when we are being grossly over regulated that I would be happy to see its use forbidden except in a few licensed situations, but this may be difficult to achieve. As one who has very much specialised in making Roman candles, we have evidence that so many fires have been caused during manufacture with chlorate stars. It is so much better either not to use it or to use a delay composition which does not contain free sulphur.

The last caveat is ammonium perchlorate. I use it, but I have severe reservations about its commercial use in quantity and its long term storage. So far as the firework manufacturers are concerned I think that this is mainly concerned with the use of magnesium and chlorates in the same premises. It is fine for those of us who are chemists for we are continually aware of the problems but I am not so sure about this at shop floor level. One factory in England which no longer is in business made stars with both potassium chlorate and barium chlorate and also with ammonium perchlorate. The materials were always kept separate and a building was set aside for the ammonium perchlorate. However the stars got mixed in shells and rockets. The factory was flooded one winter in exceptional conditions and all the stock in the magazines was wet. When the floods went down the magazines blew up one at a time as they dried out.

It makes you think.

UN OUTIL INDUSTRIEL DE SECURITE

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RESUME

La construction d'un outil industriel de sécurité repose sur une analyse détaillée dont le but est de réduire la probabilité d'occurrence d'un accident et la gravité de cet accident lorsqu'il se produit.

Cette analyse permet de définir un outil de fabrication assurant la sécurité des opérateurs et garantissant un niveau constant de qualité des produits fabriqués.

La démarche est illustrée par des réalisations de Ruggieri concernant la fabrication d'étoiles et le chargement de bombes : pour chaque cas traité après un survol rapide de la technologie du procédé, on montre les résultats acquis en matière de sécurité de fabrication et sur la qualité du produit fabriqué.

INTRODUCTION

Avant de songer à construire un outil industriel de sécurité, il convient de se fixer l'objectif de sécurité que l'on cherche à atteindre : la sécurité absolue n'existant pas, il faut accepter un certain niveau de risque. Mais ce risque doit être parfaitement identifié, et maîtrisé.

L'objectif de sécurité va être fixé en tenant compte des nombreuses obligations réglementaires qui régissent l'industrie pyrotechnique et tout particulièrement la fabrication des artifices de divertissement. Mais le cadre réglementaire ne peut être considéré que comme un minimum qui doit être complété par un objectif industriel propre à l'entreprise.

L'objectif que s'est fixé Ruggieri est, non seulement, de réduire la fréquence et la gravité des accidents de personne mais, aussi, d'assurer la pérennité de l'outil de travail quels que soient les aléas de fabrication. La rigueur imposée dans la maîtrise de ces risques conduit à des définitions les plus précises possible des conditions de travail et à la vérification constante de la conformité au modèle de départ : ceci conduit tout naturellement à des produits de qualité bien définie et reproductible.

Après avoir brièvement exposé la méthode de travail qui permet de construire un outil industriel de sécurité, nous l'illustrerons par deux exemples pris dans la fabrication d'étoiles et de bombes d'artifices.

COMMENT CONSTRUIRE UN OUTIL INDUSTRIEL DE SECURITE ?

La fonction des substances pyrotechniques est de se décomposer rapidement, sous une sollicitation adéquate, pour libérer de l'énergie. Dans le cas des artifices de divertissement, cette énergie se retrouve sous forme de bruit (onde de choc) ou de lumière et chaleur (flux thermique).

A partir de ce constat, on peut déjà dresser les grandes lignes de la méthode :

- d'abord il faut connaître la sensibilité intrinsèque des compositions pyrotechniques aux sollicitations fonctionnelles ou aux agressions accidentelles les plus fréquentes,

- ensuite, il faut pouvoir comparer ce niveau de sensibilité au niveau des sollicitations et agressions imposées par les processus de fabrication,

- puis il faut identifier et maîtriser le régime de décomposition des produits pyrotechniques en tenant compte de l'environnement réel dans lequel ils se trouvent lors des différentes phases de fabrication,

- enfin il faut savoir protéger les personnes et, si possible, l'outil de travail pour que si, malgré tout, un incident se produit, sa gravité en soit la plus faible possible.

La méthode mise en oeuvre par Ruggieri permet de répondre successivement à ces questions à partir d'une approche essentiellement expérimentale.

Connaître la sensibilité des produits pyrotechniques

Les sollicitations et agressions les plus fréquentes dans les procédés de fabrication sont mécaniques (choc, friction), thermiques, électriques (électricité statique) ou chimiques (compatibilité entre les composants et avec l'humidité).

Les différentes méthodes expérimentales de détermination de la sensibilité des compositions pyrotechniques sont bien connues, l'objet n'est pas de rappeler ici les modes opératoires utilisés mais d'exposer quelques réflexions sur la question.

Le caractère même des compositions pyrotechniques fait que, à performances constantes, il est souvent difficile d'agir sur les seuils de sensibilité.

Pourtant, on sait que l'augmentation de la granulométrie des constituants élémentaires réduit la sensibilité des produits (aux agressions nécaniques mais surtout à l'électricité statique), que le travail en phase liquide diminue la sensibilité des compositions, etc.

Il n'y a guère que l'utilisation d'inhibiteurs volatils qui soit possible mais encore faut-il qu'ils soient compatibles avec les constituants (le moins cher, l'eau, est rarement utilisable dans les compositions pour artifices de divertissement) et leur utilisation peut conduire à des séchages, parfois à des températures élevées induisant d'une part un risque thermique et d'autre part un coût de fabrication plus élevé.

Puisque les moyens d'actions sur la sensibilité des compositions pyrotechniques sont limités, il va falloir agir sur les niveaux de sollicitations et d'agressions auxquels les compositions peuvent être soumises pendant la fabrication.

Réduire le niveau des agressions fonctionnelles et accidentelles

Tout procédé de fabrication induit des contraintes sur le produit :

- contraintes mécaniques :
  - . friction lors du tamisage,
  - . friction lors des mélanges et malaxages,
  - . friction et choc lors du découpage,
  - . friction et confinement lors de la compression,
  - . etc,

- contraintes thermiques pendant toutes les phases de fabrication à température supérieure à l'ambiante (pouvant être accentuées par d'éventuelles réactions exothermiques entre les composants),

- contraintes électriques : générations de charges électrostatiques lors des écoulements de matières, des tamisages, des mélanges, etc.

La connaissance précise des caractéristiques fonctionnelles des matériels et des contraintes induites permet d'estimer le niveau des agressions que vont subir les produits pyrotechniques pendant la fabrication. Cette connaissance permet d'orienter le choix du matériel de fabrication.

En comparant les valeurs de ces contraintes aux seuils de sensibilité des compositions, on peut alors définir une marge de sécurité. Dans cette approche, une difficulté d'interprétation survient souvent car la détermination des seuils de sensibilité des compositions pyrotechniques ne porte, en général, que sur de petits échantillons et ne tient pas compte d'un éventuel effet de masse : des essais sur maquette à échelle 1 s'avèrent alors souvent nécessaires.

A ces agressions fonctionnelles du procédé peuvent venir s'ajouter des agressions accidentelles dues à des dérives du procédé, elles doivent être prises en compte dès la conception des appareillages.

Ces dérives peuvent être, par exemple :

- une augmentation anormale de la température en cas de défaillance de la régulation thermique,

- des frottements intempestifs (défaut de coaxialité piston/matrice lors de la compression, frottement des pales sur les parois d'un malaxeur, modification de l'état de surface par corrosion des parois internes des cuves et autres conteneurs, etc).

La maîtrise des dérives du procédé est un des éléments primordiaux pour garantir un outil industriel de sécurité. Les défaillances doivent donc être prises en compte dès la conception des appareillages. Y pallier totalement nécessite une parfaite connaissance de la fiabilité des matériels. Ceci n'étant pas toujours possible a priori il faut prévoir une procédure détaillée d'entretien préventif (fréquence et nature des examens en fonction de la vulnérabilité des produits pyrotechniques).

Identifier et maîtriser les régimes de décomposition

A l'air libre, sans confinement, le régime de décomposition des compositions pyrotechniques pour artifices de divertissement est, dans la plupart des cas, la combustion. Mais lorsque la masse de composition augmente ou lorsque le confinement devient plus important, le régime de combustion peut transiter vers un régime de décomposition accompagné d'un effet de souffle pouvant être important.

Pour assurer la sécurité des installations, il est donc indispensable de connaître et de maîtriser les conditions limites en deçà desquelles le risque de transition peut être évité.

Ces conditions limites sont obtenues expérimentalement par des essais de détermination de la hauteur critique d'explosion (recherche de la hauteur de composition au delà de laquelle la décomposition se fait avec effet de souffle, l'essai s'effectue dans un tube d'acier cylindrique, la composition est initiée par le bas du tube).

Pour de nombreuses compositions (par exemples compositions à taux de magnésium supérieur à 40 % ou à taux de chlorate supérieur à 30 %) il suffit d'une hauteur de 10 à 20 cm pour que la décomposition prenne un régime explosif. L'effet de souffle peut alors être compris entre 50 et 100 % de ce que donnerait une masse équivalente de trinitrotoluène.

Ces déterminations indispensables ne sont pas toujours suffisantes. En effet, lorsque la géométrie de l'appareillage de fabrication s'éloigne de la forme cylindrique, il est souvent utile de confirmer les résultats de hauteur critique par des essais en maquette à échelle 1.

Enfin, lorsque le régime d'explosion est atteint pour des hauteurs trop faibles par rapport aux impératifs de la fabrication et, si pour des raisons de sécurité on veut éviter les conséquences d'un effet de souffle, reste à étudier la possibilité de limiter les risques de transition grâce à des évents. Ceux-ci par leur rupture en cas de prise en feu vont brutalement diminuer le confinement, permettant ainsi d'éviter les surpressions qui auraient pu conduire à l'explosion en masse.

Protéger les personnes et l'outil industriel

Quelles que soient les conditions opératoires définies à partir des études qui viennent d'être décrites, le risque de combustion violente ou d'explosion doit toujours être pris en compte.

Pour protéger les opérateurs contre ces risques résiduels, il convient de pouvoir les éloigner le plus possible du siège éventuel de l'accident.

Ceci conduit, en fait, à rechercher des procédés automatiques ou semi-automatiques.

L'automatisation des procédés de fabrication des artifices de divertissement implique certaines contraintes :

- les paramètres physiques des matières premières, des produits intermédiaires et des produits finis doivent être correctement maîtrisés. Selon la phase du procédé, il peut s'agir de la granulométrie, de la viscosité ou de la coulabilité, de l'état de surface, de la densité, des dimensions, etc. Les paramètres physiques de l'environnement (température, humidité) doivent également pouvoir être régulés.

- des détecteurs d'évènements intempestifs doivent être placés aux points clés de l'appareillage ; les signaux doivent être transmis rapidement au cerveau de la machine pour que les mesures compensatoires puissent être prises sans retard.

- quelle que soit l'efficacité de ces détections, il faut souvent maintenir la possibilité pour l'opérateur d'une observation directe du procédé (ceci est réalisé soit par l'aménagement de hublots préalablement calibrés à travers les parois fortes soit par l'utilisation de caméras vidéo automatiques).

En résumé, l'automatisation de la fabrication des artifices de divertissement oblige à une meilleure connaissance du procédé, à une estimation correcte des divers paramètres liés aux produits et à la machine, à une maîtrise des dérives de l'ensemble de ces éléments. Ceci conduit à une meilleure reproductibilité du produit fabriqué. Ainsi l'automatisation permet non seulement de travailler avec un niveau de sécurité satisfaisant mais encore de garantir un niveau de qualité constant des produits fabriqués.

DEUX EXEMPLES D'OUTILS INDUSTRIELS DE SECURITE

La méthode de travail décrite a été mise en application pour la fabrication des compositions pyrotechniques, pour celle des étoiles et autres sous-ensembles des artifices et pour celle des artifices eux-mêmes.

Afin de l'illustrer, nous avons choisi deux exemples. Le premier concerne la fabrication des étoiles sphériques à la dragéifieuse et le second la fabrication de bombes de calibre 50 et 75 mm.

Fabrication d'étoiles sphériques

(photographies 1 et 2)

La fabrication des étoiles sphériques à la dragéifieuse se fait à partir d'un "germe", pyrotechnique ou non, enrobé de couches successives de composition pyrotechnique jusqu'à l'obtention d'étoiles de dimension préalablement définie. La composition pyrotechnique peut être la même tout au long de l'opération ou varier en cours de fabrication pour obtenir, par exemple, des étoiles à changement de couleur.

Dans ce procédé, la composition sèche ou préalablement mouillée est introduite automatiquement dans la dragéifieuse par l'intermédiaire d'une trémie équipée de son système de dosage et de distribution. Les agents de mouillage et les autres composants liquides sont également introduits automatiquement dans la dragéifieuse à partir de réservoirs et de systèmes de distribution adéquats.

Lors de la mise au point de ce procédé, il a fallu se poser un certain nombre de questions quant à la sécurité de fabrication :

a/ Quelles sont les caractéristiques pyrotechniques intrinsèques des compositions ?

Les compositions pyrotechniques mises en oeuvre sont, selon leur composition chimique, des matières classées en division de risque 1.3 (risque de combustion avec rayonnement thermique important) ou en division de risque 1.1 (risque d'explosion, le pic de pression dû à l'explosion pouvant être compris entre 25 et 75 % de celui qui résulterait d'une masse équivalente de tolite).

Ces compositions lorsqu'elles sont sèches sont, pour la plupart, très sensibles aux agressions mécaniques (choc essentiellement) et à la décharge électrostatique. Le choix judicieux de l'agent de mouillage peut permettre de diminuer la sensibilité des compositions.

b/ Quel est le comportement des matières pyrotechniques dans le système ?

Pour définir la masse de composition pyrotechnique pouvant être introduite sans risque dans la trémie d'alimentation, il a fallu rechercher la hauteur en deçà de laquelle le produit conservera en toute circonstance un régime de combustion. L'utilisation de trémies évasées et à parois faibles a permis d'optimiser cette valeur.

La même démarche a été effectuée pour définir la masse maximale pouvant être admise dans la dragéifieuse.

c/ Quel est le niveau des agressions provoquées par le système ?

La nature même du procédé de dragéification fait que les contraintes mécaniques fonctionnelles sont extrêmement limitées, d'où l'intérêt de ce mode de mise en oeuvre pour les compositions pyrotechniques particulièrement sensibles à l'impact.

Mais la distribution des compositions pyrotechniques par écoulement ou le mouvement de la matière dans la dragéifieuse sont des opérations qui génèrent des niveaux de charges électrostatiques importants. Certains types de compositions (ainsi que les solvants) ayant des seuils de sensibilité à la décharge électrostatique faibles (inférieur à 50 mJ), il a fallu particulièrement veiller au piégeage et à l'écoulement des charges électrostatiques.

d/ Comment protéger les opérateurs ?

Par l'optimisation des masses des produits et par l'adaptation des appareillages au comportement des produits, il a été possible de réduire la probabilité d'occurrence d'un évènement indésirable et d'exclure un régime d'explosion au cas où cet évènement se produirait. Mais les quantités mises en oeuvre sont telles que le dégagement thermique en cas de prise en feu serait très important.

Ceci a conduit à installer le pupitre de commande de l'installation dans un local séparé de la dragéifieuse par un mur fort (la surveillance se fait par vision directe à travers hublot et par caméra vidéo orientable).

Fabrication de bombes

(Photographies 3 à 9)

Une bombe est constituée de deux parties : un culot contenant la charge propulsive et un coffre contenant la charge d'éclatement et les étoiles destinées à produire l'effet. Ces deux parties sont reliées pyrotechniquement entre elles par une "espolette" destinée à transmettre l'initiation avec un retard prédéterminé. La charge propulsive est initiée par une mèche d'allumage ou un inflammateur électrique.

La fabrication d'une bombe comprend les phases suivantes :

- montage de l'espolette sur le culot,
- mèchage du culot,
- garnissage du culot de poudre propulsive (poudre noire),
- garnissage du coffre des étoiles et de la charge d'éclatement (poudre noire ou autre composition pyrotechnique),
- fixation du culot sur le coffre.

Les compositions de propulsion et d'éclatement sont sensibles à de nombreuses agressions (choc et étincelle électrostatique en particulier) et appartiennent à la division de risque 1.1 (avec un équivalent tolite en pic de pression de 0,5 pour la poudre noire et de l'ordre de 0,75 pour les autres compositions pyrotechniques).

La fabrication manuelle des bombes en grandes séries impose, à chaque poste de travail, des quantités importantes de plusieurs types de poudre noire, de compositions pyrotechniques et d'étoiles. En cas d'incident, de probabilité non négligeable compte-tenu de la sensibilité de certains de ces produits, il est alors difficile de pouvoir prétendre protéger efficacement l'opérateur. Cette constatation a conduit Ruggieri à étudier la mise au point d'un procédé de fabrication dans lequel les matières pyrotechniques sensibles sont toujours séparées de l'opérateur par des écrans à l'efficacité contrôlée.

Pour ceci, deux concepts étaient envisageables :

- concevoir une machine fonctionnant en continu et placée derrière une barrière de béton suffisamment résistante pour contenir les effets d'une explosion simultanée de la totalité des compositions pyrotechniques,

- ou bien prévoir une machine fonctionnant par séquences et pour laquelle chaque opération élémentaire se déroule dans un alvéole séparé des voisins par une cloison telle que le risque d'explosion simultanée de l'ensemble des compositions pyrotechniques puisse être écarté.

C'est cette seconde solution qui a été retenue.

La machine de chargement automatique des bombes se compose des sous-ensembles suivants :

a/ Une bande transporteuse animée d'un mouvement pas-à-pas permanent de fréquence réglable. Cette bande est équipée de supports destinés à recevoir alternativement les coffres vides et les culots équipés de mèche et retard pyrotechnique. La bande est approvisionnée manuellement par un opérateur. La partie accessible est séparée de la partie active de la machine par un blindage métallique de 8 mm d'épaisseur muni de hublots d'observation.

b/ Des postes de chargement séparés les uns des autres par des murs de béton et constitués chacun de trois parties :

b1/ Une loge d'alimentation :

Elle est munie d'une porte légère qui permet son accès depuis la coursive de desserte. Elle est séparée de la loge de dosage décrite en b2 par un mur de béton équipé d'une porte blindée.

Son équipement est constitué par :

. un support bidon : sur lequel l'opérateur est chargé de positionner un bidon de composition. Un contrôle étanchéité, obligatoire pour la poursuite de la logique de la chaîne, permet d'assurer que le bidon est correctement positionné et fermé sur son support.

Le support est placé sur un axe vertical à entrainement magnétique qui permet d'amener le bidon de composition au niveau de la trémie d'alimentation. Une sécurité interdit tout mouvement du support lorsque la porte est ouverte. Un témoin "défaut bidon" indique à l'opérateur qu'il faut approvisionner un bidon de composition.

. Une trémie d'alimentation : destinée à collecter le contenu du bidon de composition. Cette trémie est reliée à un récupérateur de poussières (conteneur plastique avec réserve d'eau ou d'un liquide approprié compatible avec les compositions).

. Un sas de communication : qui permet l'approvisionnement de la trémie de dosage de la loge de chargement par la trémie d'alimentation par doses fractionnées.

Une sécurité maintient ce sas nécessairement fermé lorsque la porte d'accès est ouverte.

b2/ Une loge de dosage :

Elle est séparée de la loge d'alimentation par un mur de béton équipé d'une porte blindée et de la loge de transfert par un blindage métallique de 8 mm d'épaisseur lui aussi équipé d'une porte blindée.

Une sécurité interdit l'accès du personnel dans cette loge lorsque le système est en fonctionnement.

Son équipement est constitué par :

. Une trémie de dosage chargée de remplir les éléments de bombe avec la quantité adéquate de produit. Un détecteur de niveau procède à l'arrêt de la chaîne (après exécution du pas en cours) lorsque la trémie est vide.

. Une trappe de communication entre la loge de dosage et la loge de transfert qui permet le chargement de l'élément de bombe.

b3/ Une loge de transfert :

Elle est séparée de la loge de dosage et de la partie externe de la bande de transport par un blindage métallique.

Cette loge abrite la bande transporteuse. Elle est équipée :

. d'un bras de préhension destiné à amener et à positionner l'élément à charger sous la trémie de dosage (par l'intermédiaire de la trappe de communication située dans la loge de dosage),

. de deux trappes d'alimentation qui isolent la partie de bande transporteuse, située dans le poste de chargement considéré, de l'ensemble des autres postes.

c/ Un poste d'assemblage de la bombe :

Selon le type de bombe, l'assemblage se fait par vissage ou par collage et encliquetage. Ces opérations automatiques se font dans un alvéole séparé des voisins par un blindage métallique.

d/ Un poste d'étiquetage de la bombe.

Cette machine de chargement automatique des bombes constitue un outil industriel de sécurité efficace, en effet :

- Elle permet de mettre en oeuvre des compositions pyrotechniques sensibles en exerçant sur elles des contraintes fonctionnelles parfaitement définies et donc contrôlables.

- Aucun personnel n'est directement présent lors des phases de fabrication où s'exercent ces contraintes (jamais le personnel n'est en contact avec des matières pyrotechniques nues : l'alimentation de la machine consiste simplement à déposer un bidon de composition sur la machine, les transvasements se faisant automatiquement).

- Le mode de fonctionnement séquentiel avec décomposition de chaque opération permet de ne mettre en oeuvre dans un local donné que les quantités de matières pyrotechniques juste nécessaires à l'opération en cours et donc de limiter les conséquences néfastes d'un accident.

- les risques de propagation sont réduits par l'utilisation systématique d'alvéoles de travail n'autorisant le transfert des produits de l'un à l'autre que lorsque chaque opération élémentaire de chargement est terminée.

Cet outil industriel de sécurité présente également des avantages induits qui méritent d'être soulignés :

- L'automatisation nécessite des matières premières aux caractéristiques physico-chimiques parfaitement définies et reproductibles. Cette contrainte sur les conditions de fabrication a un impact positif sur la qualité du produit fini.

- L'automatisation, avec tous les contrôles intégrés qu'elle nécessite, assure une excellente reproductibilité des bombes fabriquées et donc, là encore, une qualité du produit fini parfaitement reproductible.

- Enfin le chargement automatique des bombes permet un gain de productivité important (avec deux opérateurs, ce type de machine a une production moyenne de 400 bombes par heure).

CONCLUSION

On a vu dans tout ce qui précède que la construction d'un outil industriel de sécurité nécessite une volonté affirmée de l'entreprise et impose des investissements importants.

Ces investissements portent d'abord sur toutes les étapes de définition des appareillages et de leur mise au point (Les approches théoriques et les calculs doivent être confirmés par des essais souvent coûteux).

L'investissement matériel est également très important : la nécessaire fiabilité des machines impose de nombreux systèmes de contrôle, et le découplage peut imposer des structures lourdes.

Mais ces investissements, quel que soit leur prix, ont des effets dont l'intérêt est évident.

D'une part ils permettent la mise en oeuvre de produits plus sensibles, et donc plus performants, tout en assurant une sécurité accrue au personnel de fabrication.

D'autre part, ils concourent à une amélioration sensible de la qualité des produits fabriqués grâce à la reproductibilité qui découle des conditions de fonctionnement d'une installation automatique parfaitement contrôlée.

Un produit de qualité aux performances bien définies et reproductibles est donc la conséquence toute naturelle de l'utilisation optimisée d'un outil industriel de sécurité.

Fabrication d'étoiles sphériques a la dragéifieuse

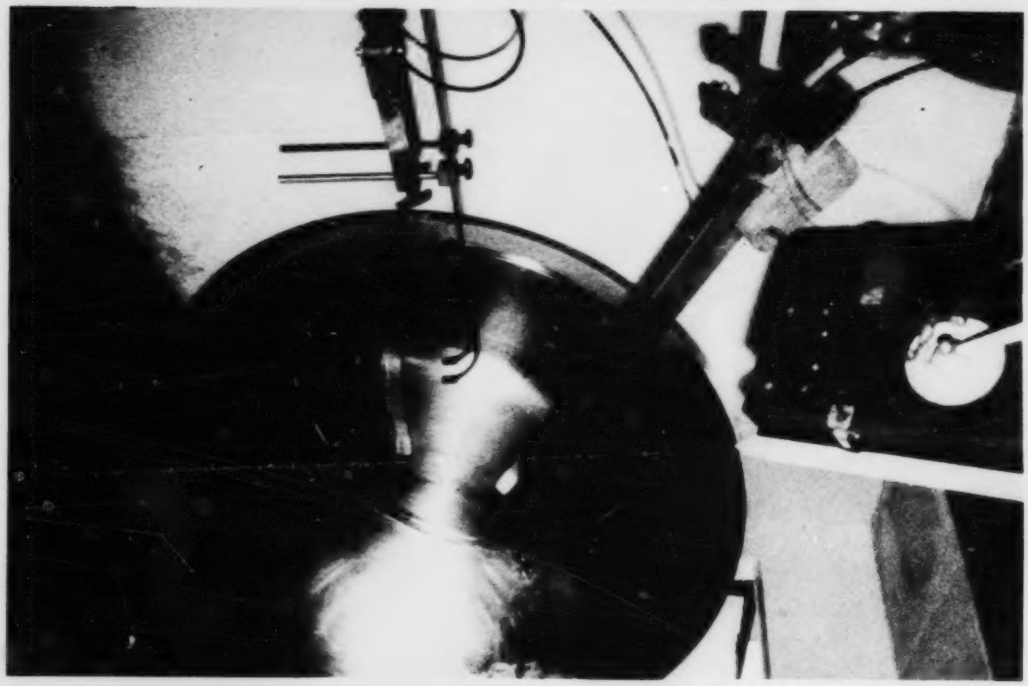

Fig. 1 - Dragéifieuse avec système de distribution automatique des compositions pyrotechniques et des solvants

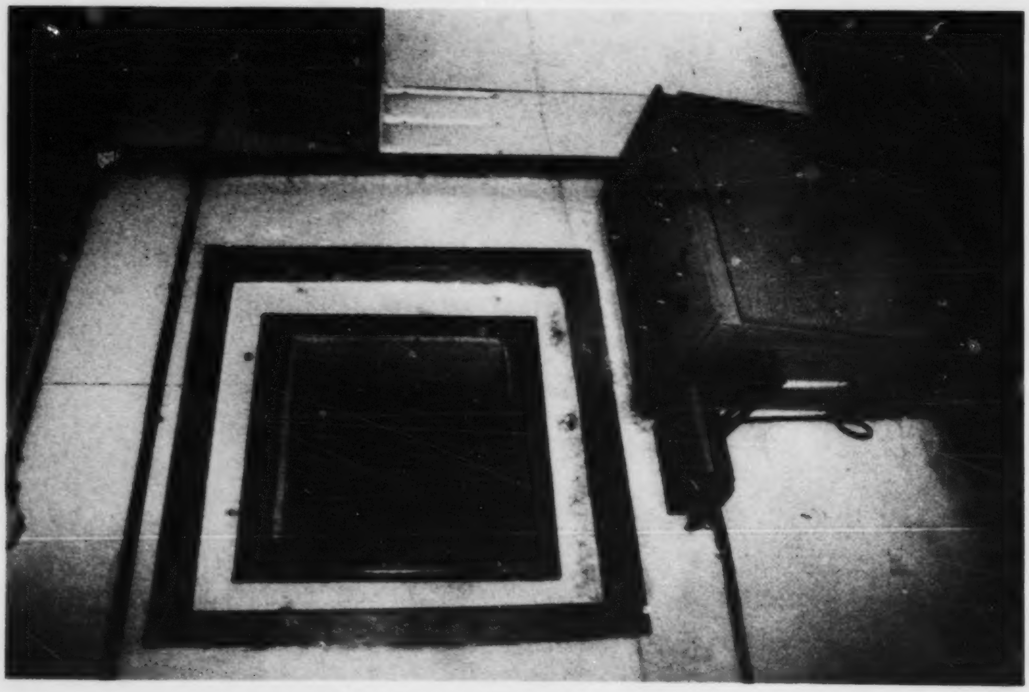

Fig. 2 - Poste de commande de la dragéifeuse

Fabrication des bombes

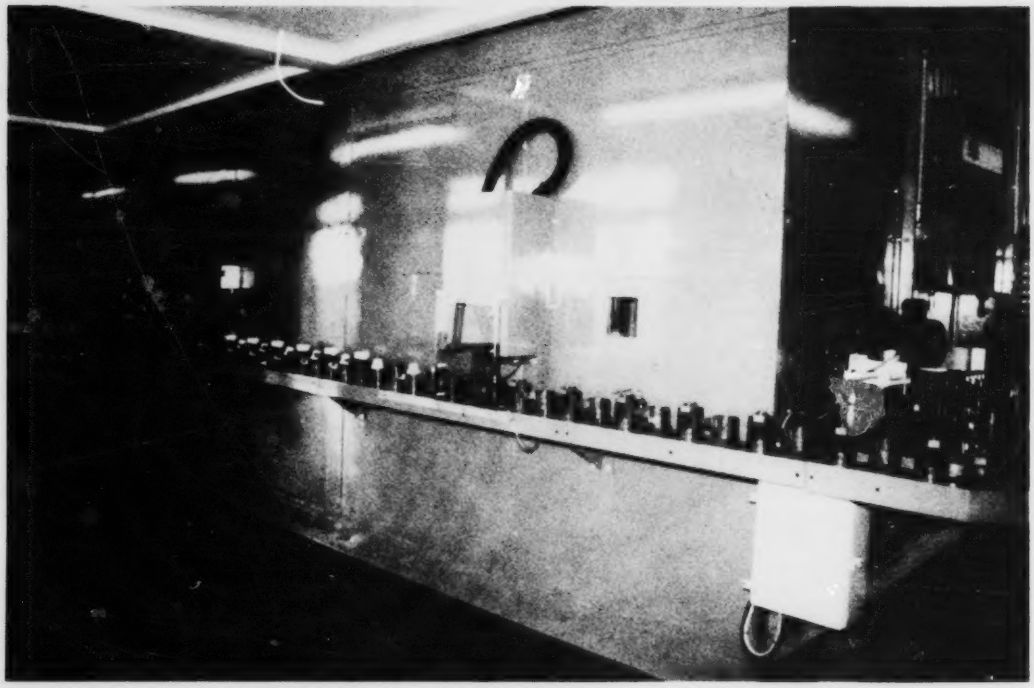

Fig. 3 - Bande transporteuse (partie accessible aux opérateurs)

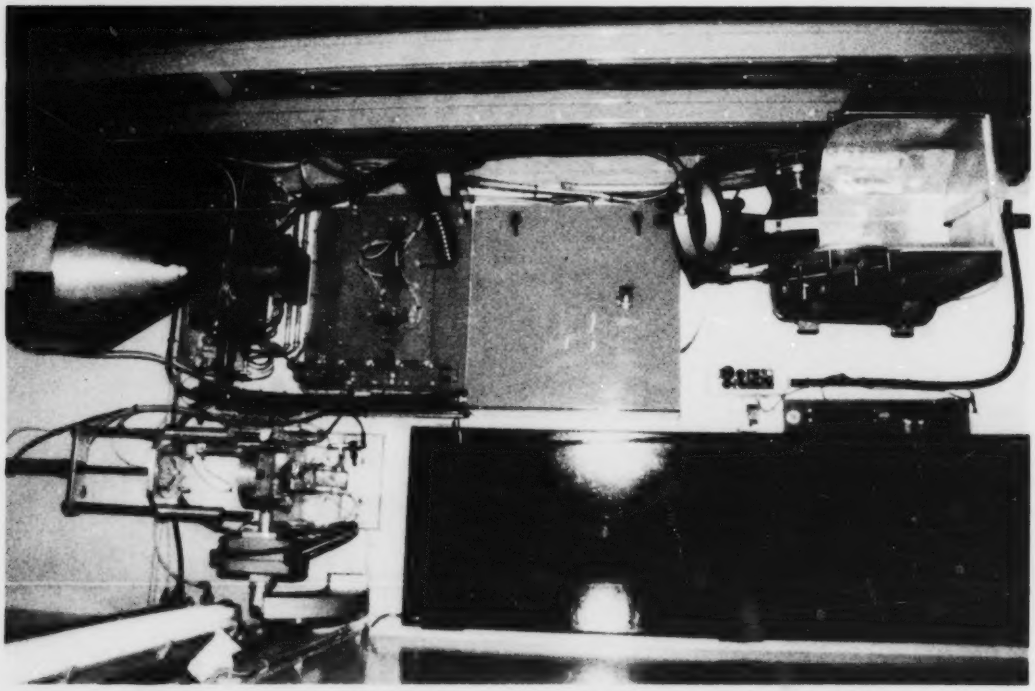

Fig. 4 - Loge d'alimentation avec système de transfert du bidon de composition et trémie d'alimentation

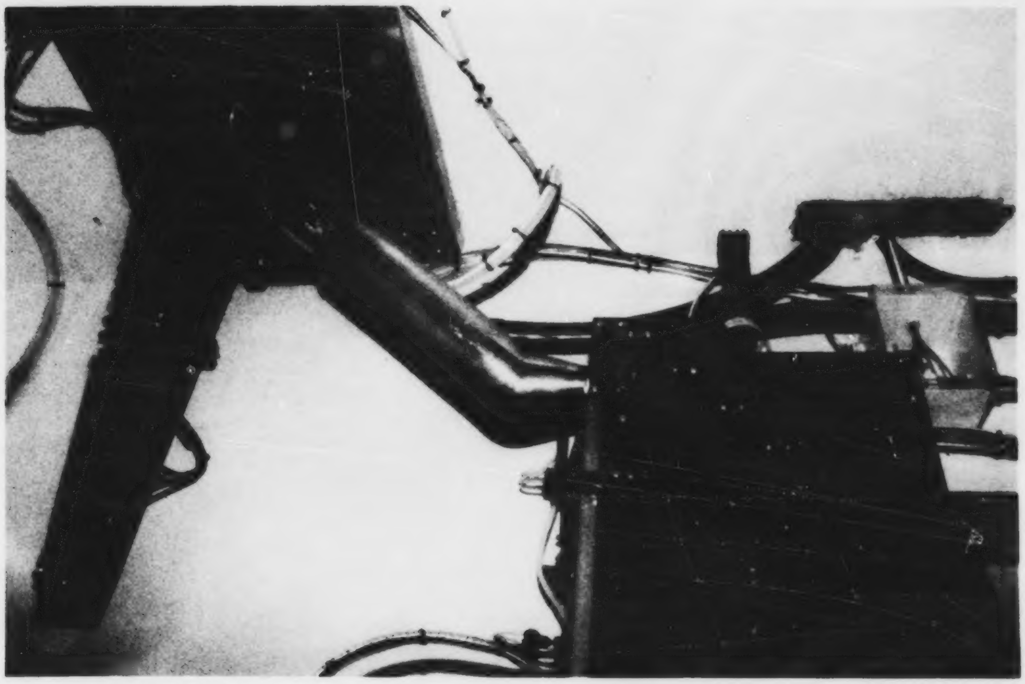

Fig. 5 - Loge de dosage

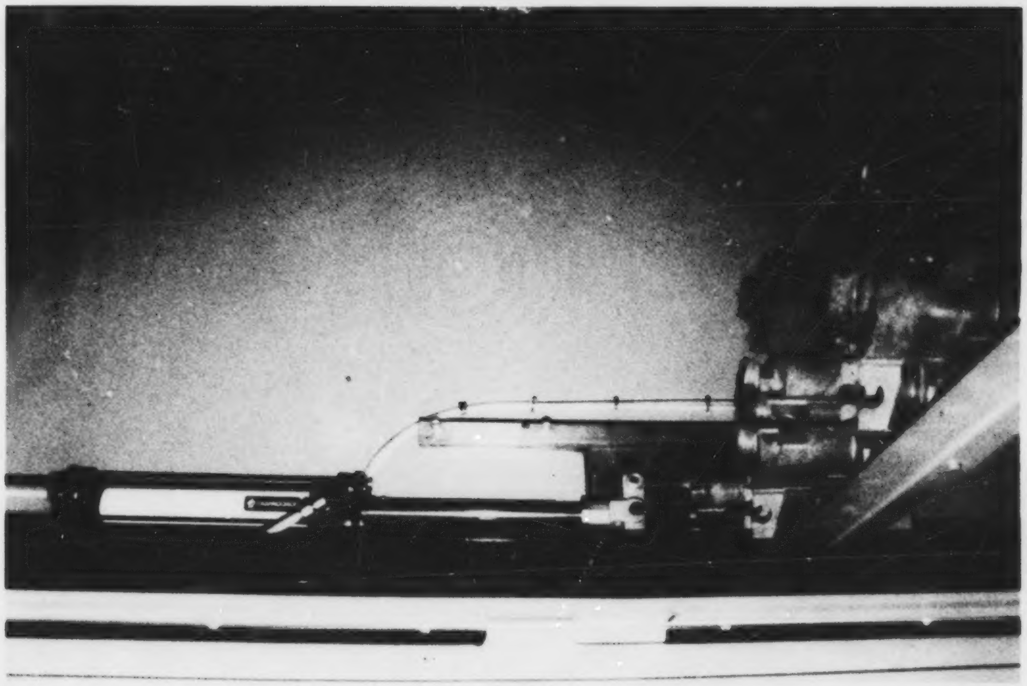

Fig. 6 - Bande transporteuse dans la loge de transfert

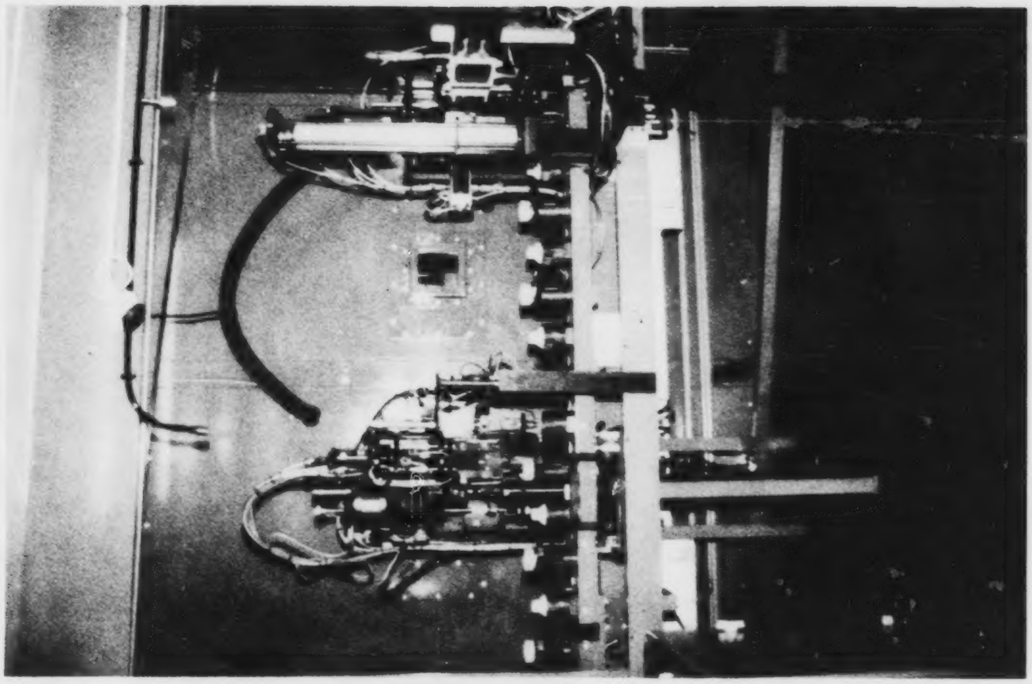

Fig. 7 - Poste d'assemblage

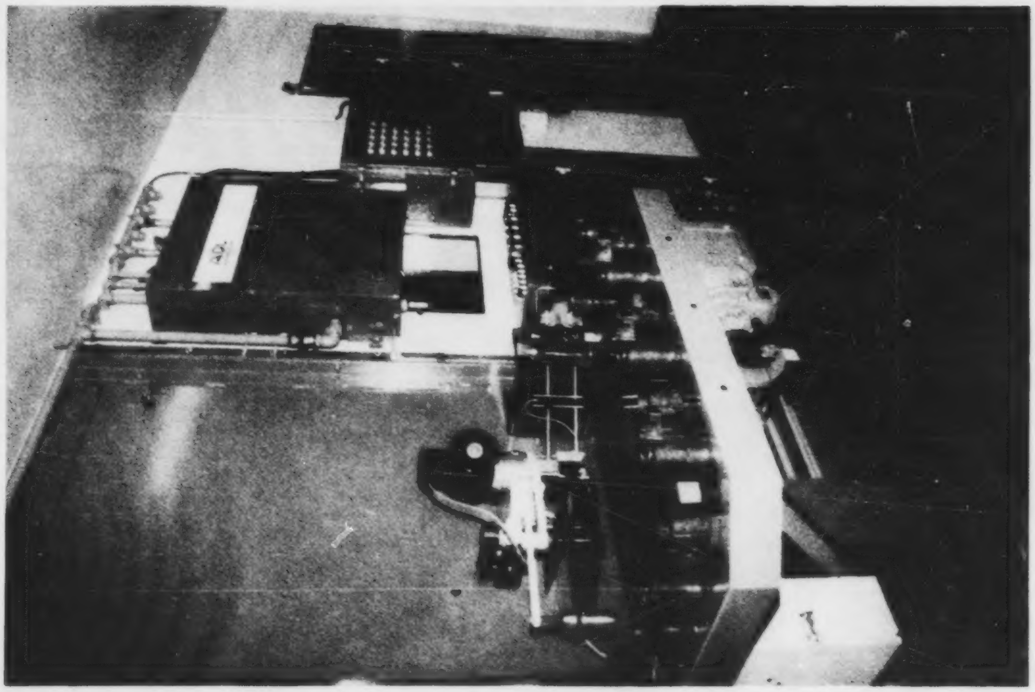

Fig. 8 - Poste d'étiquetage et poste de commande de la machine

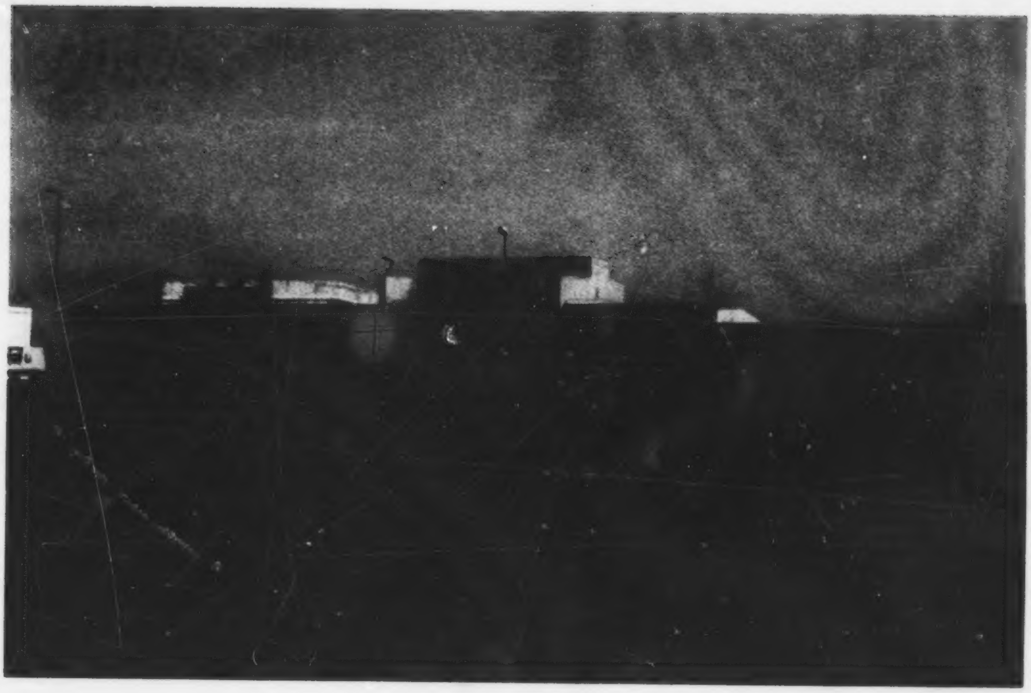

Fig. 9 - Vue générale du bâtiment

ILLEGAL PYROTECHNICS MANUFACTURED

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ABSTRACT

In 1984, the Bureau of Alcohol, Tobacco and Firearms (ATF) initiated an Illegal Explosives Interdiction Project which was designed to monitor investigations concerning the illegal distribution of M-80's. The objectives of this project are to identify the problems associated with the investigation of clandestine firework factories; to recognize the violations of Federal laws as they pertain to clandestine firework factories; to describe the methods used by illegal manufacturers to distribute their products; and finally, to describe the georgraphical areas within the United States where clandestine firework factories are located.

INTRODUCTION

The manufacture and distribution of illegal explosive devices continues to pose a challenge to both the law enforcement and regulatory agencies of the United States government. The Bureau of Alcohol, Tobacco and Firearms is confronting this challenge, however, through effective liaison, media support, and aggressive law enforcement, and is proving that a significant impact can be made.

Jurisdiction over M-80's and similar devices is the responsibility of the following agencies: (1) the Bureau of Alcohol, Tobacco and Firearms (ATF); (2) the Department of Transportation, Office of Hazardous Materials Regulation (DOT); (3) the Consumer Product Safety Commission (CPSC).

In 1984 ATF initiated its Illegal Explosives Interdiction Project, which was designed to monitor investigations concerning the illegal distribution of M-80's. Illegal pyrotechnic devices encountered in the United States by ATF agents have steadily increased in the last few years. Accidents involving illegally manufactured pyrotechnic devices have been monitored since 1970. During a 13 year period from 1978 to 1990 ATF statistics from investigations into illegal M-80 manufacture reveal a total of 780 investigations involving 48 explosions, 54 fatalities and 131 injuries as a result of illegal M-80 factories. In addition property damage was estimated in excess of $20.2 million. The National Response Team was activated on eight of those occasions where explosions occurred.

Education of field agents in the danger of raids on illegal manufacture of M-80's is important as they are classified as high explosives and not "firecrackers." Manufacture of M-80's is a high-profit business that thrives mainly in the mid-west and the north-eastern parts of the United States.

ATF's experience has shown that a raid upon an illegal explosive device factory can be one of the most dangerous operations in which a special agent can participate. An investigator should approach an investigation with as much awareness as possible of the M-80 manufacturing process and the hazards caused by the careless storage of chemicals and explosive mixtures at these plants. The lack of quality control in the manufacturing process and the complete neglect of basic explosive safety standards often leads to catastrophic conditions. Unfortunately, these clandestine factories have been located in shopping centers, business and residential areas.

LEGAL FIREWORKS INDUSTRY	
EXPLOSIONS	43
KILLED	45
INJURED	141
DAMAGE	$6,171,600
NRT	4

ILLEGAL FIREWORKS INDUSTRY	
EXPLOSIONS	38
KILLED	45
INJURED	91
DAMAGE	$13,800,000
NRT	7
CRIMINAL INVESTIGATIONS	499

A HISTORY OF FIREWORKS

A review of recreational fireworks development

by

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INTRODUCTION

"What are Fireworks like? " the princess asked the prince one morning as she was walking on the terrace. "They are like the Aurora Borealis." said the King, "Only much more natural. I prefer them to stars myself, as you always know when they are going to appear." From the Remarkable Rocket by Oscar Wilde.

Fire has been the most important element in the development of mankind. In the early stages of man, it was the possession of fire that distinguished him from the lower forms of life. Fire has made human life possible in areas of the earth where, without it, his existence would be impossible. The benefits and protection it has afforded us are immeasurable, perhaps more than those of any other element. The mere increase in the population of the world owes its success to the use and control of fire. Above all, fire has been the most important stimuli to man's creative genius.

We do not know when men first achieved the art of fire making, but we are sure that every race and tribe had to use it to survive. At first, ignition was obtained from natural sources, such as forest fires, volcanoes and molten sulphur pits. The making of fire must have been one of man's first inventions and was probably regarded as a feat of magic. Its association with the sun and stars and other heavenly bodies soon gave it a religious significance. There are very few religions indeed in which fire in some form or other doesn't play an important role. The burnt sacrifice, the burning of incense, candles, and the burning of bamboo are just a few. One main benefit bestowed upon mankind by fire is its association with the art of cooking. As salt and other ingredients were discovered it seems likely that recipes evolved and were used in cooking. The art of pyrotechnics probably owes its inception to this fact.

In parts of Asia,remote from the sea, the formation of saltpeter occurs in surface deposits. It was used, and still is, as a salt substitute and for preserving meats. Imagine the first observation when a quantity of nitrate fell into the cooking fire. This must have been an early lesson in applied chemistry as the embers would spark and crackle from the addition of the nitrate. Another example would be preparing a fire on a nitrate deposit for the evening meal; imagine the astonishment when the right combination of heat, fuel and oxygen intermixed. "Poof". The possibility of using coal, charcoal, sulphur, and other combustibles along with saltpeter would suggest itself. Here is gunpowder in its earliest form. When exactly this event took place no one really knows but before recorded history. Where this event first took place seems to point to China, Egypt, India, Arabia and Greece.

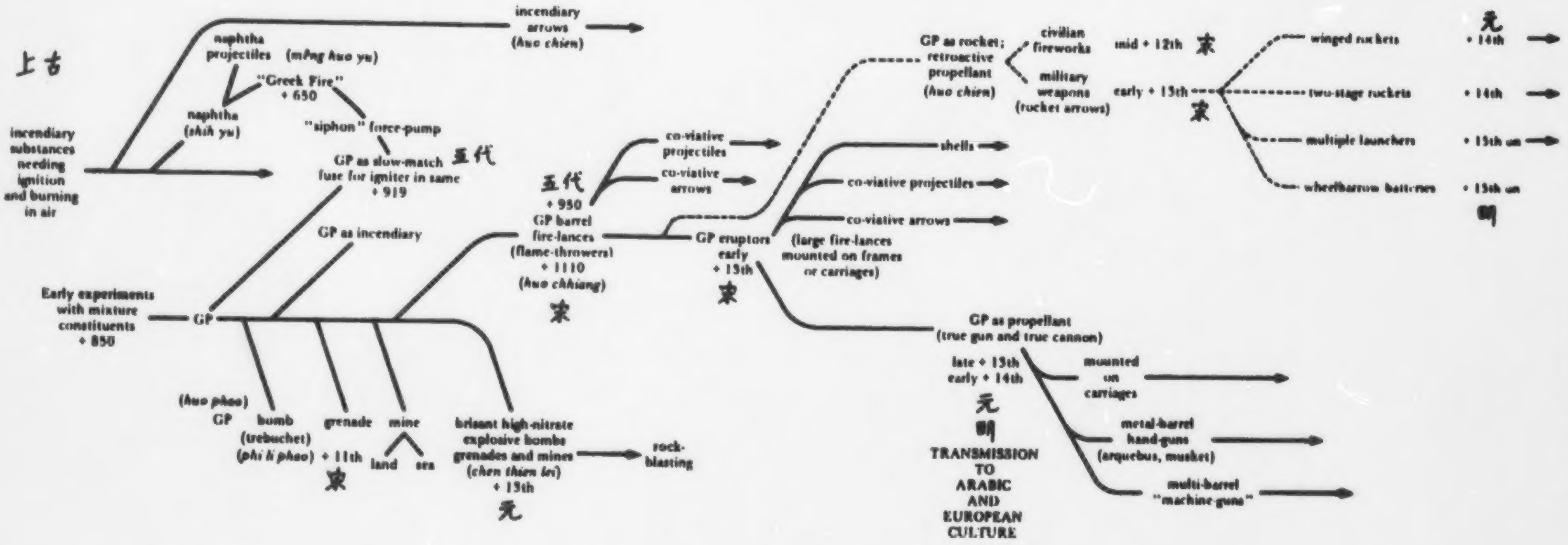

上古
incendiary substances needing ignition and burning in air
naphtha projectiles
(mêng huo yu)
"Greek Fire" + 650
naphtha (shih yu)
"siphon" force-pump
GP as slow-match fuse for igniter in same + 919
五代
incendiary arrows (huo chien)
GP as incendiary
Early experiments with mixture constituents + 850
GP
(huo phao) GP
bomb (trebuchet) (phi li phao)
+ 11th
宋
grenade
mine
land
sea
brisant high-nitrate explosive bombs grenades and mines (chen thien lei) + 13th
元
rock-blasting
五代
+ 950
GP barrel fire-lances (flame-throwers) + 1110 (huo chhiang)
宋
co-viative projectiles
co-viative arrows
GP eruptors early + 13th
宋
shells
co-viative projectiles
co-viative arrows
(large fire-lances mounted on frames or carriages)
GP as rocket; retroactive propellant (huo chien)
civilian fireworks
mid + 12th
宋
military weapons (rocket arrows)
early + 13th
宋
winged rockets
two-stage rockets
multiple launchers
wheelbarrow batteries
元
+ 14th
+ 14th
+ 15th on
+ 15th on
明
GP as propellant (true gun and true cannon)
late + 13th
early + 14th
元
明
TRANSMISSION TO ARABIC AND EUROPEAN CULTURE
mounted on carriages
metal-barrel hand-guns (arquebus, musket)
multi-barrel "machine-guns"

Fig. 1. Chart to illustrate the development of gunpowder technology.

The earliest forms of fireworks may simply have been molten sulphur thrown in the air, or burning of other combustibles under controlled conditions. The use of Greek fire thrown by catapult, or primitive fire pumps must have produced spectacular displays. But these and other early pyrotechnic devices were used for war not rejoicing. The first displays for rejoicing were created by priests and magicians. The fire altars of ancient Egypt, India and China held spectators in awe when early powders and fireworks devices were used to gain influence over the people. These early pyrotechnists appeared to have supernatural powers as they created puffs of smoke, flames, and noise at will. Surely this was communication with the gods. The art probably developed independently in many eastern countries, but according to available data the Chinese did it first. Around 400 B.C. the Chinese were already using incendiary compositions as weapons. These were made by combining nitrate, sulphur, charcoal, powdered iron, resins, poisonous materials, as well as animal droppings and urine. These mixtures were used in rockets, fire arrows, and in bamboo containers that were shot or thrown at the enemy. The designs were many and all were intended as weapons of destruction. These early pyrotechnists had no idea that their devices would evolve as an art form. Since the Chinese also invented printing and paper, their secrets were preserved for future generations to use.

There has been much debate over gunpowder as to its discovery and its role in pyrotechnics. Some of the early Chinese manuscripts (A.D. 618 to 906) make reference to huo shu (fire trees) and yin hua (silver sparkle). These are believed to be claims for fireworks. The Wu Yuang of Lo Ch'i (14th century) says that fireworks of gunpowder were first used by the Sui emperor Yang Ti (A.D. 603 to 617). The words huo yao appear in Chinese poetry in A.D. 600 which means fire chemical and the taoist alchemist Ko Hung refers to shiao shih (saltpeter) in A.D. 265. Wang Ling said that under the North Sung Dynasty (A.D. 960 to 1126) a new type of cracker is mentioned P'ao Chang (exploding bamboo). He also suggests that this cracker contained gunpowder and had a new shape. They were connected by continuous fuse so they could explode one after another. It is important to note that the Chinese burned bamboo to obtain the cracks and pops to ward off evil spirits such as the monster Nin of the forest. These were not gunpowder crackers but joints of bamboo thrown on hot fires. This custom was said to derive from Buddism in the A.D. 6. When the Chinese added huo yao to these natural bamboo containers Nin must have run for the hills. At the same time, any malfunctioning tubes would fly thru the air erratically like unstabilized rockets or spew out fire dust, thus suggesting early pyrotechnic fountains. Bamboo tubes were used up until the 1920s to produce Chinese fireworks (see museum exhibit).

From 1275 to 1292 Marco Polo, along with his father and uncle, lived in China. He witnessed first hand the many inventions of pyrotechnics for recreation and war. He says if the young green canes are put on a campfire "they burn with such a dreadful noise they can be heard for ten miles at night and anyone who is not use to it could die, hence the ears are stuffed with cotton and clothes drawn over the head and the horses are tied on all four feet with their ears and eyes covered for it is the most terrible thing in the world to hear for the first time." Surely Polo was referring to gunpowder explosions. When Polo returned to Italy, he brought examples of his new discoveries. Europeans were amazed and excited over such devices as rockets, crackers, and fountains loaded with Chinese fire composition. He also caried pasta back with him. But just as pasta was rumored to have been made in southern Italy before Polo introduced it, there were also suggestions of gunpowder development in Europe.

A manuscript entitled *Leber Ignium* by Marcus Graecus (Mark the Greek), which is assumed to have been written in 1225 or 1300 has been used as evidence to substantiate the knowledge of gunpowder. Friar Bacon"s work, *Opus Majus* also claims the knowledge of gunpowder, but all this evidence is sketchy and it appears that there is little doubt that the origin of gunpowder and fireworks was in the east. It was probably, discovered rather than invented. Berthold Schwarz a 13th century, Franciscan monk from Germany, perfected gunpowder manufacture as well as basic principles of the gun. But the ancestry of Schwarz is also mysterious and it has been said that he may have been Asiatic. After this 13th and 14th century period, the development of pyrotechnics for pleasure slowly developed throughout Europe. The end of the 13th century maybe taken as a starting point and there are substantial grounds for placing its birthplace in Italy. Now the Fugisti (Italian pyrotechnists) were bringing their fireworks displays to all parts of Europe. This enabled the French, German, Spanish, Portuguese, etc. to learn the art, and its secret formulas, which they in turn took with them on their journeys around the world.

The first European books to mention fireworks to appear at this time were, Battista della Valle's *Vallo Libro Continente* (1524) describes artificial fireworks, flying fish, etc. I am told that descendants of the Valle family still operate in Southern Italy to this day. Biringuccio's *Pyrotecnia* (1540) mentions fireworks and their use on feast days in Northern Italy. Most of the books that dealt with the subject that were written during this period had chapters on fireworks as well as artillery. Eventually books were published exclusively on the manufacture of recreational fireworks. One of the first was written by Schmidlap in 1560 *Artificial and Honest Fireworks for Joy* which boasted of material never before being printed. Its description said that even if you had no previous experience, this book could educate anyone in the art of making fireworks. Ufano's book *Tratado de la Artilleria* (1612) has five chapters devoted to fireworks. He describes horizontal and vertical wheels, flying dragons and line rockets.

John Bate published his mysteries of nature and art in 1635. The second of four books stated "teaching most plainly and with all most exactly the composing of all manner of fireworks for triumph and recreation." At this point Europeans were taking fireworks on their journeys to all parts of the world. The Dutch introduced fireworks to Japan around 1610 and had them on their ships when they landed at Plymouth Rock in 1620. The Spanish also carried pyrotechnics to many of the lands that they conquered.

Finally we get to Babington's *Pyrotecnia* of 1635, the first book in English to deal exclusively with fireworks. Babington held a unique place in pyrotechnic literature for the next 70 years. Then came Frezier's *Traite des Feux d' Artifice* (1706), the first French work on the subject. In 1749 the first Italian work was written by Alberti, *La Pyrotechnia*. Giuseppe Alberti's book deals exclusively with the subject of fireworks for pleasure. It has many improvised techniques and formulas that rivaled pyrotechnists from the same period.

During this same period the famous Ruggieri family from Bologna, Italy, were gaining popularity. In 1739 they put on a spectacular display in Versailles and for the next decade they grew more popular with each display. One of their many achievements was to create fabulous set pieces that utilized new techniques. They were the first to use metallic salts to impart color in their formulas. It must be kept in mind that this is before chlorate color formulas had been invented. The Ruggieri's also were the first to use ammonium chloride which greatly assisted color production formulas. This was a major step foward in European pyrotechnics (see attachment).

For the next forty years there were many attempts to create color formulations. But not until 1786, when Berthollet prepared potassium chlorate, did the pyroytechnist have the right chemical compound for his formulas. This new oxymuriate of potash, as it was called then, was used in gunpowder formulations and early percussion systems with disastrous results. One of the first formulas using potassium chlorate to appear in print was that of James Catbush, the famous American chemist and pyrotechnist from Phildelphia. It appeared in the American Journal of Science in 1823. It stated "besides the admixture of several saline substances which communicate, particular colors to flame, we know that the most brilliant red is obtained by the use of strontium nitrate, sulphur, potassium chlorate, and antimony sulphide". This preparation was noted by Cutbush as being used for theatrical purposes in France. It is important to note here that many pyrotechnic formulas were used by magicians and conjurors first, and then found their way into pyrotechny.

In *The Lives of the Conjurors* written by Thomas Frost in 1876 there are many revelations concerning pyrotechnics and the history of gunpowder. In a copy of *Artificial Fireworks* by Captian Jones (1776) that I possess (see attachments),there are several formulas that are hand written. For green illumination it states,

I I.

ARTIFICIER,

CONTENANT

Planches simples 3.

I I.

ARTIFICIER.

EXPLICATION.

N°. I.

LA vignette repréſente l'attelier ou le magaſin d'un artificier.

Fig. 1. Etranglement des groſſes fuſées.

2. Maniere de charger les cartouches déja étranglées. *a*, le maillet. *b*, la baguette à charger. *c*, le cartouche. *d*, ſebille où ſe met la poudre apprêtée. *g*, cuiller pour mettre la poudre dans le cartouche. *e*, mortier dans lequel ſe pilent le ſalpetre, le charbon & autres matieres qui entrent dans la compoſition de la poudre. *f*, gloire ou ſoleil d'artifice. *h*, fuſées volantes montées ſur leurs baguettes. *i*, pluſieurs fuſées liées enſemble. *l*, fuſées chargées & étranglées par les deux bouts prêtes à monter.

3. Ouvrier qui colle le cartouche.

4. Ouvrier qui pile le charbon, le ſalpetre & autres matieres.

Bas de la Planche.

Fig. 1. Baguette ou rouleau à mouler les cartouches.

2. Baguette à charger les cartouches.

3. Baguette à mouler les pots des fuſées volantes.

4. 5. 6. Maniere de coller & de mouler les différens cartouches.

23. 24. 25. 26. Baguette à charger les fuſées avec une de leur broche.

N°. II.

Fig. 27. Fuſée volante ſur ſa baguette.

32. Trois fuſées accouplées enſemble.

34. Fuſée montée ſur ſon pot.

35. Fuſée volante ſans baguette, mais avec un reſſort de fils-de-fer auquel pend un poids.

Fig. 39. Développement d'une fuſée à ſecond vol.

40. Fuſée qui en contient de plus petites à ſecond vol.

41. Fuſée garnie d'une étoile.

42. Fuſée garnie de ſauciſſons.

43. Développement d'une fuſée chargée & ſur la broche.

44. Tourniquet à un & à deux tenons, pour une ou deux fuſées brillantes ou chinoiſes.

45. Moule à faire des étoiles.

47. Etoile en fil d'étoupille pour les pots de fuſées & d'autres.

50. Fuſée montée en bruit de guerre.

51. 52. 54. 55. Différens pieds mouvans.

53. Fuſée en parapluie.

57. Poinçon qui s'allonge & ſe raccourcit.

N°. III.

Fig. 59. Fuſée qui porte un ſoleil fixe.

61. Bombe.

63. & 64. Ballons.

65. Développement d'un ballon.

65. Mortier pour tirer des bombes.

67. Développement d'un ballon qui en contient un autre.

68. Communication de deux jets d'artifice.

69. Développement d'un pot-à-feu.

70. Fuſée d'eau à ailerons.

71. Fuſée d'eau en globe.

72. Fuſée volante qui porte une gerbe.

73. Fuſée d'eau en cône.

74. Intérieur d'un ballon.

75. Genouillere.

76. Nageoire de genouillere.

77. Chevalet pour tirer & diriger les fuſées.

78. Fuſée d'eau en nageoire.

83. Pot à feu d'eau.

84. Eolipile d'artifice qui rend un ſon de gazouillement dans l'eau.

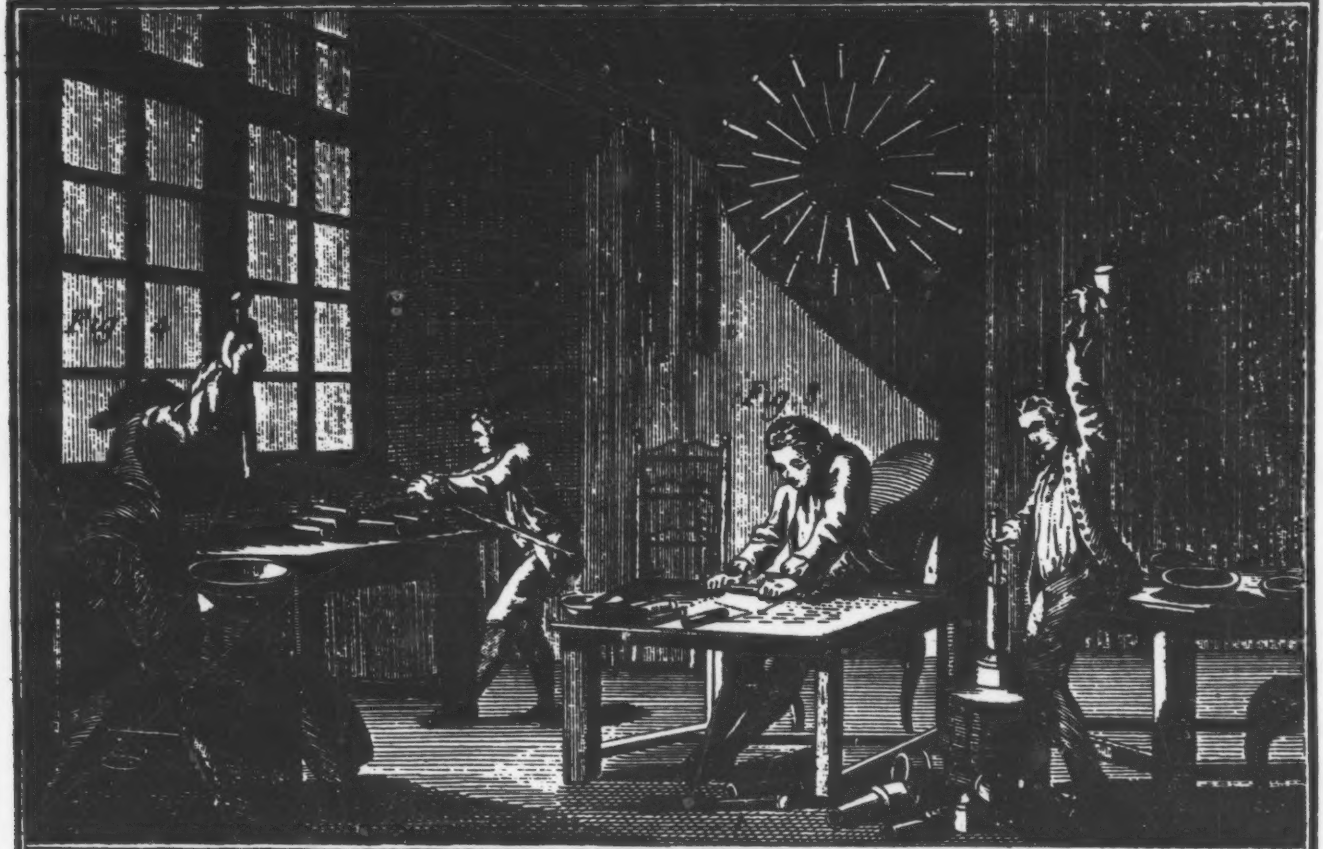
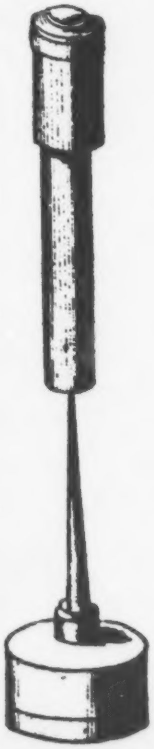


Fig. 24



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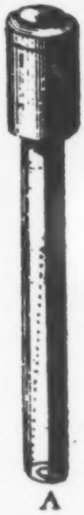

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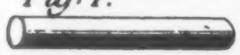

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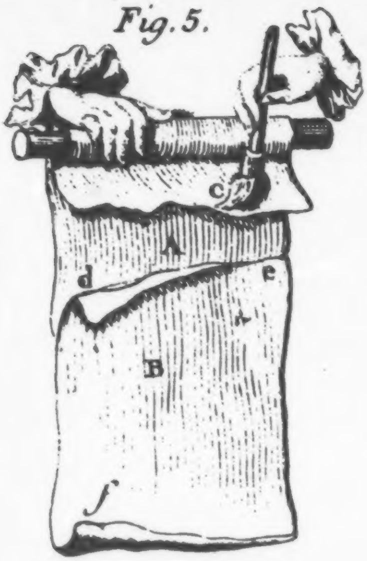

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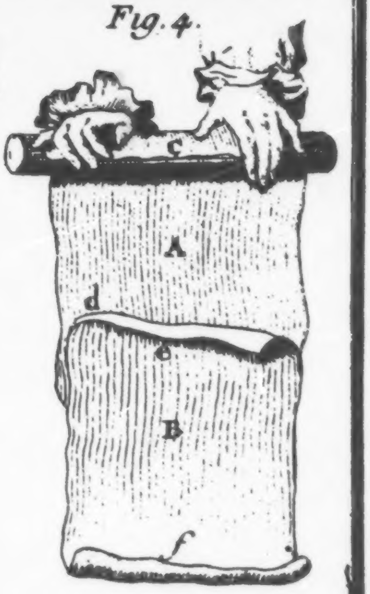
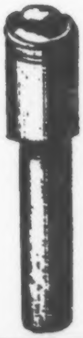


Fig. 2

Fig. 25



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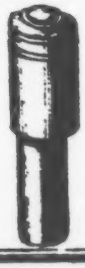

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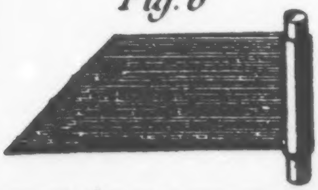


Fig. 3

ARTIFICIER.

fig. 44.

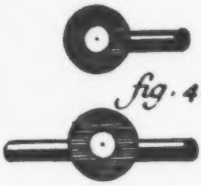
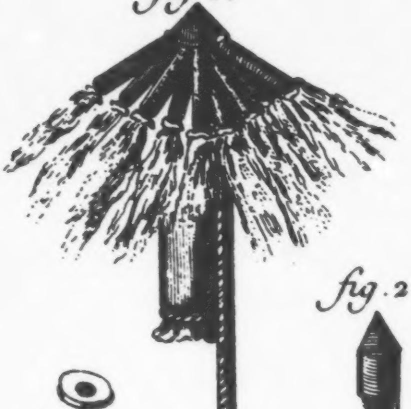


fig 53



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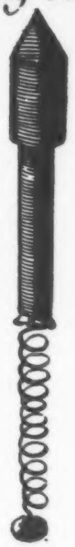

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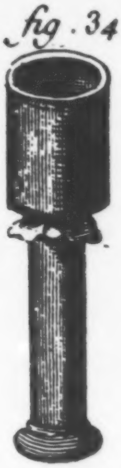

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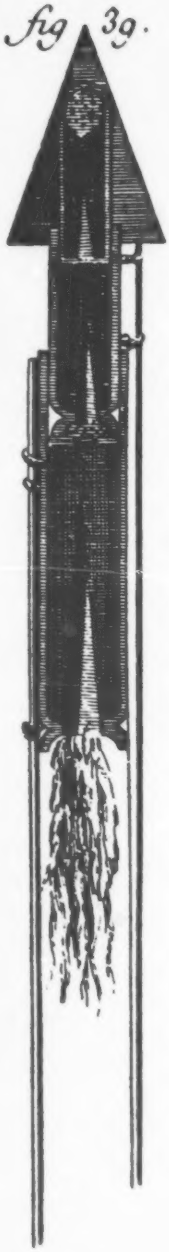

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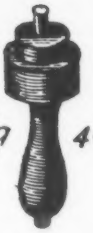

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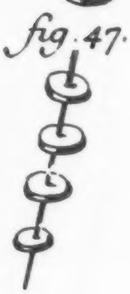

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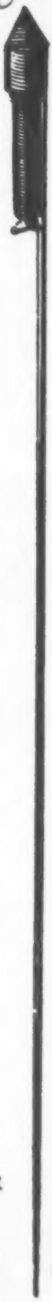

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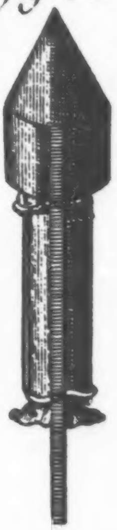

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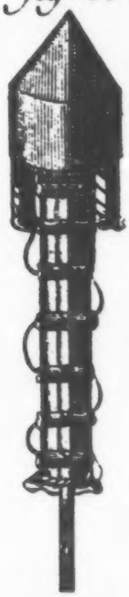

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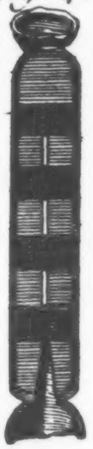

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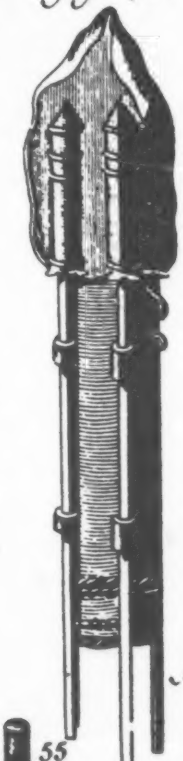

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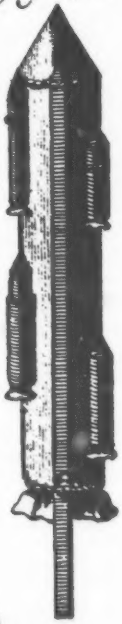

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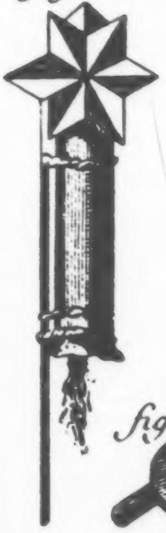

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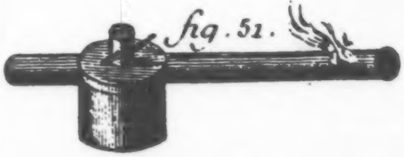

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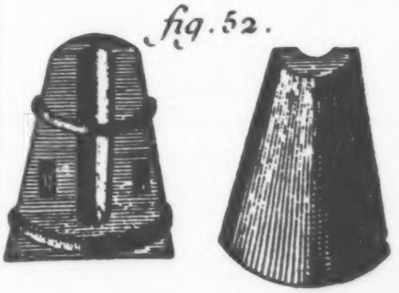

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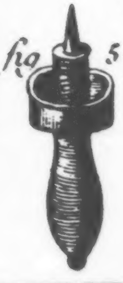

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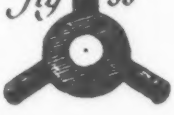

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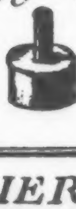


ARTIFICIER

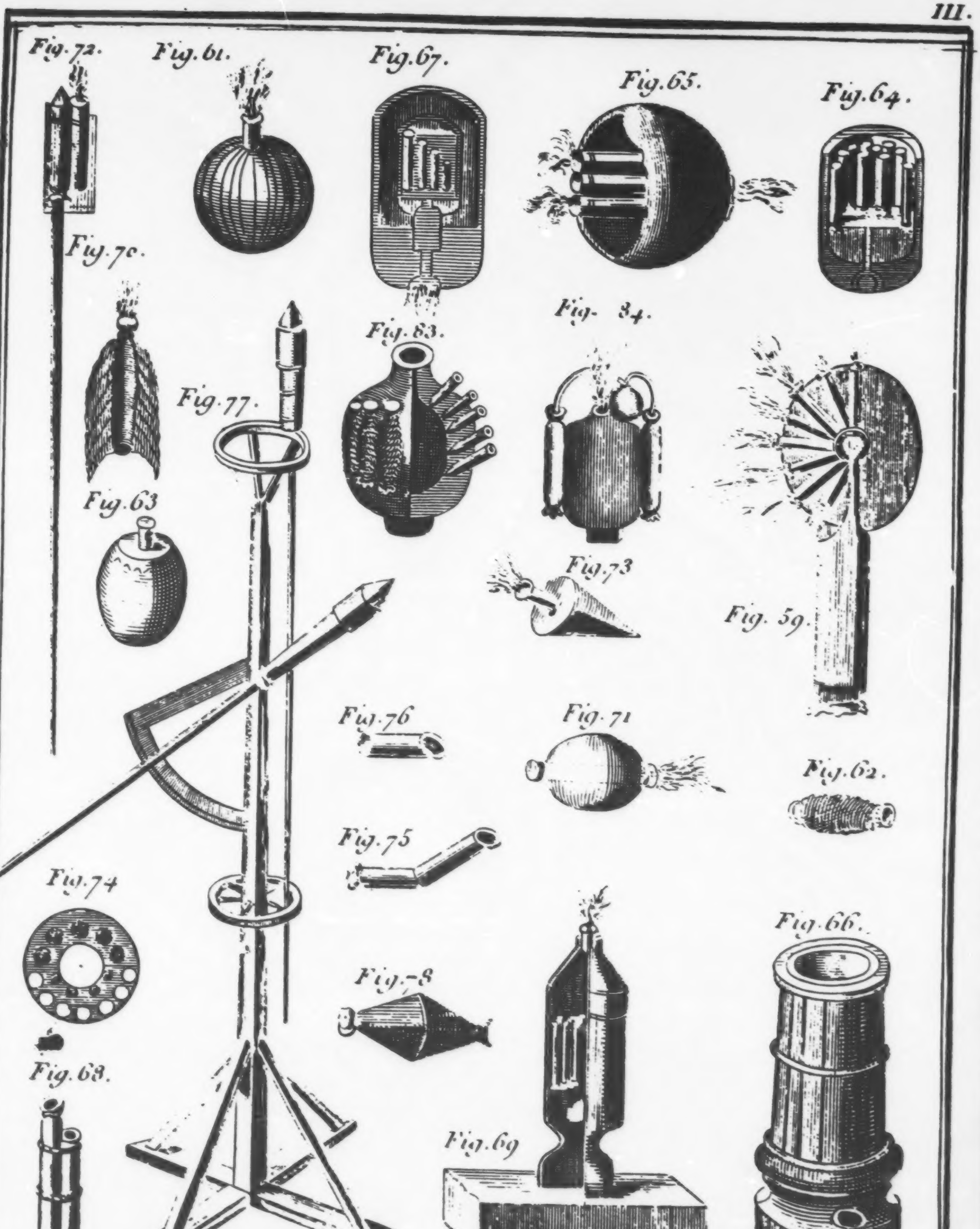


Fig. 72.
Fig. 61.
Fig. 67.
Fig. 65.
Fig. 64.
Fig. 70.
Fig. 84.
Fig. 83.
Fig. 77.
Fig. 59.
Fig. 63
Fig. 73
Fig. 76
Fig. 71
Fig. 62.
Fig. 75
Fig. 74
Fig. 78
Fig. 66.
Fig. 68.
Fig. 69

ARTIFICIER.

2 oz. potasium nitrate, 4 oz.sulphur, 2 oz. meal powder, and 8 oz. powdered zinc. The notation says that this formula was received in the year 1810 by an Italian named Petro. Another handwritten formula in the book describes red fire from Brands Journal that contains potassium chlorate, strontium nitrate, sulphur, and antomony sulphide. Another formula for green fire with potassium chlorate, metallic arsenic, barium nitrate, charcoal, and sulphur is also included. The date of these hand written formulas is 1824, which is long before the French pyrotechnist Chertier had written his book. This is very interesting because it was believed that no color formulations were in use at this time.

In 1836 Hippart published a translation of a work by Captain Moritz Meyer on the application of potassium chlorate in colored fire compositions. He describes potassium chlorate and barium nitrate for use in a formula which burns with a green flame. In the next twenty years many works dealing with pyrotechnics made their appearance. One of the most notable was by F. M Chertier. In his book *Nouvelles recherches sur les feux d' artifice* published in 1854 Chertier devotes much detail and information on the subject of color formulas. He developed a special compound known as Chertier's copper which gave great blue color but was unstable and its use was discontinued. Nevertheless, this proved to be the chemical springboard for fireworks development.

The introduction of chlorate color compositions brought the art into the spectacular age of color. This could be compared to the effect of black and white to Technicolor in the motion picture industry. Now the art of fireworks was really on its way. New and safer formulas and chemicals were constantly being created and introduced. Probably the most spectacular breakthrough was the discovery of magnesium in 1865. Its use in pyrotechnics was slow to develop because of its relative cost, but by 1880 magnesium formulas were used extensively in Europe and the U.S. for colored star compositions and flash powders. Photographers of this period used more flash powder then the pyrotechnists, which may have been an economic problem. Then in 1872 the picrates came into play which enabled the development of smokeless color compositions and the pyrotechnic whistle.

Fireworks companies were well established now in many parts of the world. Ruggieri and Aubin in France, Brock, Wilder and Pain in England, In North America, there was Consolidated Fireworks of New York run by Ditwiller and Street with their famous Unexcelled brand. The T.W. Hand Company of Canada was established in 1873, and the Excelsior Fireworks Company run by the famous pyrotechnist G.A. Lilliendahl, who was responsible for many spectacular display of the day (see attachment). The Edge family had their "First Premium Fireworks" Company of North Point, New Jersey; Masten and Wells of Boston, California Fireworks of San Francisco, Pains Manhattan Beach Fireworks, The A. L. Due, of Ohio, just to name a few. From Germany August Scharfenburg started the American Fireworks Company, and in 1864, he patented one of the first commercial loading presses to manufacture fireworks.

2 oz S. Petre
4 oz Sulpher
2 oz M, Powder
8 oz Powdered Zink

Green Illumination ——

The above was given to me by an Italian at Manchest., for a green Illumination about the Year 1810 ——

NB try it before you trust it.

Sept. 25. 1827 Mr Southby gave me the following rec.t for Tail Stars

Salt peter	16.
Antimony	8.
Brimstone	5.
Powder	12.
Coal	4½

½ Gil Linseed Oil
½ pt. Gin

Gin & oil to be well mix'd and the Comp.n to be moistned with weak Gum water fit for make into Stars.

Green fire by Sr. Petro: given to S. Gett
November 1820 in Exchange for a rect. for
yellow flame hereafter added.

The Green fire — Brimstone 4 drams
NB.
very good for — } Gunpowder 4 do
wheel cases of 4 oz } Saltpeter — ½ oz —
Zink — 2 oz —

The yellow fire —
5 parts of Nitrate of Soda
Beautiful. 1 part Sulpher
1 part Charcoal —

Red fire or the Greek fire of the Theatres

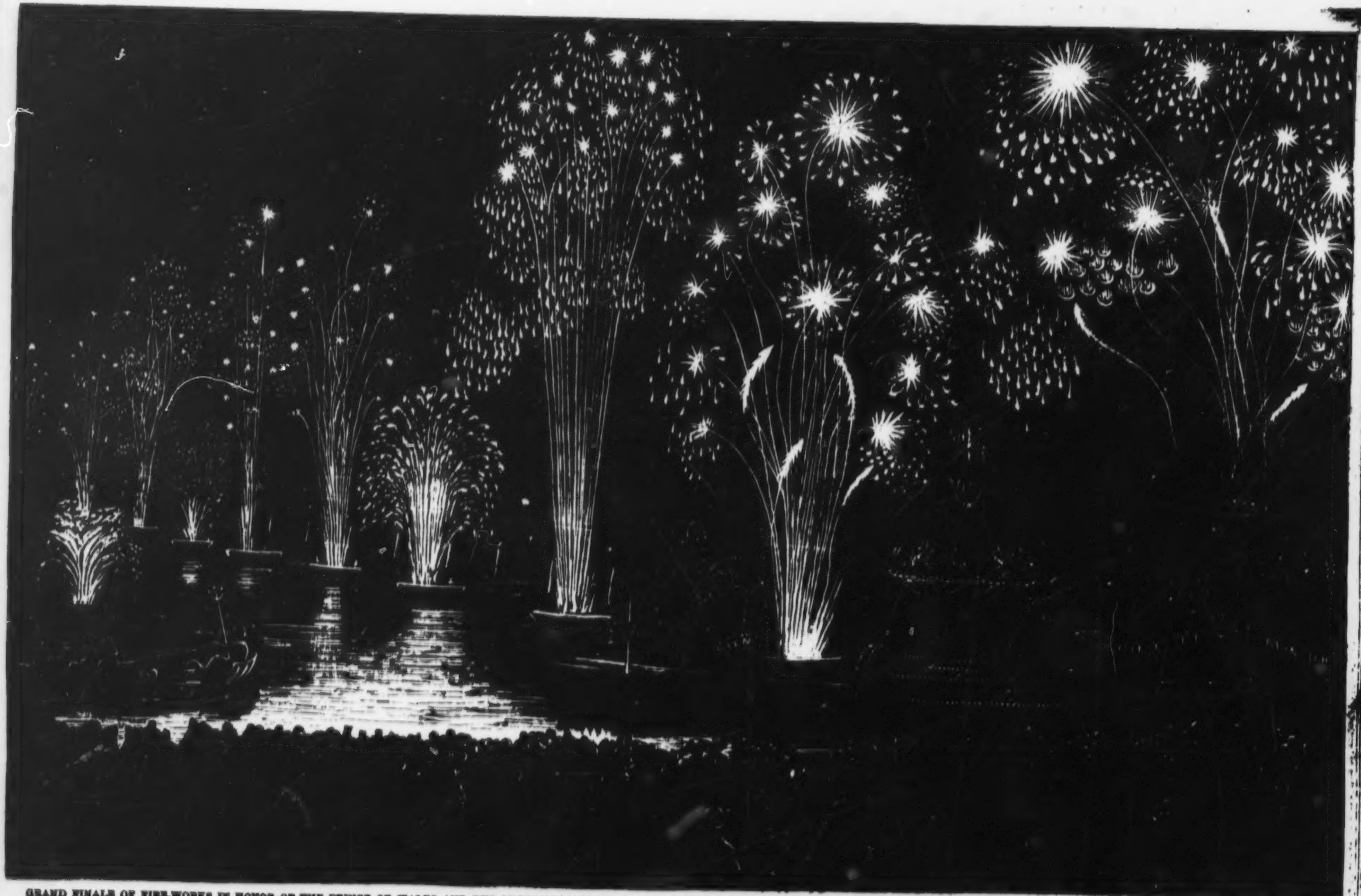
40 parts dry Nitrate of Strontian
13 parts Sulpher
5 parts Chlorate of Potash }
oximuriate of potash — }
4 parts Sulphuret of Antimony
from Brands Ch. Journal —
NB. very beautif.l Crimson red colour

Green Fire

13 parts Sulpher
77 nitrate Baryta
5 oximuriate potash
4 2 Metallic arsnic
7. 3 Charcoal —
100 from Brands Journal
Mr. Murray wrote to Mr. E. Bunting of
Mansfield for the above rect.
Feby. 4. 1824.

Thursday 2nd August 1827
Mr. Southby of No. 8. Lambeth Walk
said his rect for Rockets was 8 oz Saltpeter
2 oz Charcoal
1½ oz Sulpher
he believed there was no better. 4 oz 12 strokes
8 oz - 20 do

Pin Wheels may be moisten'd by folding them
seperately in a damp Cloth after the manner which
files are pack'd up. for a few minutes, it makes
them roll better when a small bottom is used
Southby



GRAND FINALE OF FIRE-WORKS IN HONOR OF THE PRINCE OF WALES AND THE SUCCESSFUL COMPLETION OF THE VICTORIA BRIDGE, MONTREAL, CANADA EAST, BY G. A. [illegible], ESQ., OF NEW YORK, AUGUST, 1860.

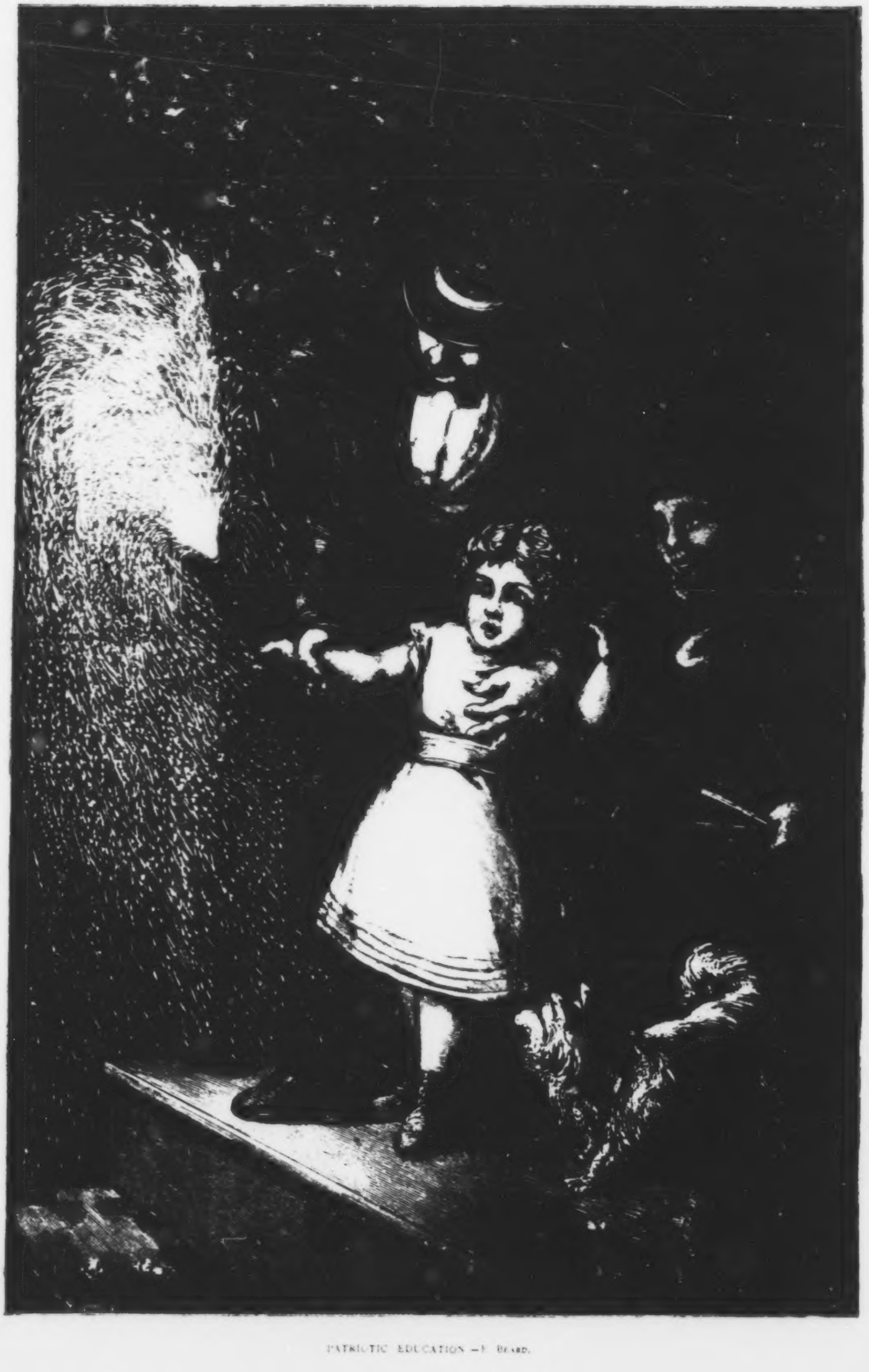
Then in 1894 aluminum made its debut, which further added to the list of pyro chemicals. Like other fireworks formulas there was not much information written about flash powders until Dr. Alfons Bujard published his *Art of Fireworks* (Stuttgart 1899). In his book he describes flash powder made with potassium chlorate and aluminum powder as being novel, but not as brilliant as magnesium flashlight powder. He also describes potassium perchlorate which would soon replace potassium chlorate in most formulas. This book was one of the first to describe flash powder and its use in photoflash photography and pyrotechnics. Another German work that I possess in my library is *Die moderne Kunstfeurerwerkerei* (Stuttgart 1913) by Dr. Gelingsheim. In this extraordinary book Dr. Gelingsheim gives formulas for glitter composition, colored flash formulations, and for the first time flash powders using the newly developed material known as Fata Morgana (magnesium/aluminum alloy) which means mirage in German.

Now new formulas and devices would be developed around the world using these new materials. As WWI approached the need for further development of military pyrotechnics increased. Some of these innovations would be used for commercial fireworks after the war. Henry Faber, Dean of the pyrotechnic schools for the U.S.government and author of *Military Pyrotechnics* (1919) created some of these unique items. He would go on to form the Tipp Fireworks Company of Ohio and introduced his new sensation the Tipp Parachute Jumper. This company would later be purchased by the Beachler family and become United Fireworks. Public and private celebrations would continue to grow around the world until WWII started. The English with their Guy Fawkes day, Dominion Day in Canada, 4th of July in the United States. New Years in Asia and Europe, feast days in Italy, Spain, Portugal, Mexico and many other latin countries.

During WWII there were virtually no fireworks to be had for public or private use, they were all used for the war effort. The second world war created new and innovative pyrotechnic systems, new binders, epoxys, fuels, and oxydizers. Then in 1947 the demand would start to increase again. More and more people would demand fireworks for their holidays and celebrations. Fireworks would soon be used for TV shows, and ammusement parks. Every tuesday night at Coney Island, the Schaefer Beer Company and the the Coney Island Chamber of Commerce would put on fantastic display. This was not unique to the US or Coney Island. Just about every country in the world had their Coney Island.

Fireworks use and development continues to grow to this day with new and safer manufacturing techniques, chemicals, and formulas. New organizations as well as old ones have played an important role in the preservation of this great artform and science. It is the responsibility of all of us that are involved in the industry to convey this knowledge into the next century.

FROM THE EIFFEL TOWER, REMAINS OF THE 1889 PARIS FAIR, A BURST OF FIREWORKS OPENS THE 1937 PARIS FAIR



PATRIOTIC EDUCATION.—F. Beard.

Everytime freedoms bell rings anywhere in the world the celebration of freedom has no greater expression than with fireworks. "When the walls come down the rockets go up".

Fireworks will be here forever!

...........be bright and busy
While hoaxed astronomers look up and stare
From tall observatories, dumb and dizzy
To see a Squib in Cassiopeia's Chair!
A serpent wriggling into Charle's Wain!
A Roman Candle lighting the Great Bear!
A Rocket tangled in Diana's train,
And Crackers stuck in Berenice's Hair!

Ode to Madame Hengler, Firework-maker to Vauxhall
by THOMAS HOOD.

FINIS

ENSEMBLE DE LANCEMENT

DE FEUX D'ARTIFICES

"ELFE D'ART

by

Robert Maurel
Societe Maurel Pyrotechnic
59, rue Voltaire
84122 Pertuis CEDEX, France

ENSEMBLE DE LANCEMENT DE FEUX D'ARTIFICES

"ELFE D'ART"

ROBERT MAUREL

INTRODUCTION

ELFE D'ART est un ensemble étudié pour simplifier l'exécution d'un spectacle d'art pyrotechnique.
Ce spectacle comprend habituellement:
-L' annonce
-Plusieurs tableaux avec effets au sol ou aériens
-Plusieurs intermèdes
-Un bouquet final
Ces différents effets sont créés à partir de bombes, marrons d'air,chandelles, jets ,gerbes etc....qui nécessitent des moyens de mise à feu importants.
Ces procédés d'initiation mobilisent des moyens considérables en personnel,et matériels pour leur mise en oeuvre.
Le système ELFE D'ART permet de s'affranchir de la lourdeur de mise en oeuvre et d'exécution du spectacle

METHODE

L'intérêt principal de l'utilisation d'ELFE D'ART permet de supprimer totalement toutes liaisons filaires qui parcourent habituellement le terrain entre les différentes pièces d'artifice.
En effet ELFE D'ART autorise la transmission entre le pupitre de mise à feu, et la ou les pièces d'artifices, grâce à une transmission en impulsions codées en modulation de fréquence bidirectionnelle.
En outre, l'invention prévoit des ensembles ou batteries dénommées "SATELLITES" qui commandés à distance, permettent le tir de projectiles aériens, mais aussi la mise à feu classique d'éléments, par inflammateurs électriques reliés aux satellites.
Dans l'exposé qui suit sont présentés les différents éléments du système ELFE D'ART.

LE SATELLITE

La batterie de tir dénommée dans l'invention "SATELLITE" consiste en une platine mécanique portant, en partie supérieure, les embases destinées à recevoir les mortiers (par exemple 2 fois 8) et, en partie inférieure les initiateurs et l'électronique associée.Cette platine sert de couvercle à un coffre qui supporte l'ensemble, assure sa rigidité et protège les dispositifs de commande et de puissance.Le coffre réalisé en acier inoxydable est muni de raidisseurs qui supportent les réactions produites par le fonctionnement des artifices.(voir photo)

Les dimensions d'un SATELLITE à 16 mortiers de calibre 50 à 150mm sont: 1200 x 230 x 260 mm
La masse du satellite sans mortiers est de 44 Kg
Poids des différents mortiers fonction de leur diamètre et de la matière

	acier inox	épaisseur	hauteur
Diamètre 50mm	1050 g	2mm	400mm
Diamètre 75mm	1570 g	2mm	400mm
Diamètre 100mm	2080 g	2mm	400mm
Diamètre 125mm	3000 g	2mm	500mm
Diamètre 150mm	4650 g	2mm	600mm

(A noter un gain de poids de plus de 50% par rapport au matériel traditionnel.)

Le nombre maximum de satellites pour une centrale est de 250 environ avec la possibilité d'augmenter encore cette capacité.

Nous avons étudié différents schémas de fonctionnement au niveau des initiateurs.Nous pouvons proposer 3 types d'architectures d'électrodes suivant la nature des compositions pulvérulentes à initier.

Suivant les divers modes d'étanchéité du mobile et les diverses applications civiles ou militaires il est possible d'adapter encore l'architecture des électrodes afin de répondre aux exigences spécifiques des compositions à initier.

L'ARTIFICE

Les artificiers que nous sommes n'ignorent pas la complexité de la conception courante d'une bombe de feu d'artifice avec par exemple sa mèche sous conduit qui, allumée à l'extérieur du mortier entre dans celui-ci, contourne le projectile pour aller enflammer la poudre de chasse propulsive.
Le décalage entre les allumages successifs de chaque bombe chargée en batterie est obtenu à l'aide de retards pyrotechniques variables et d'une précision aléatoire,qui sont les systèmes le plus couramment employés.
Tous ces inconvénients, très connus des hommes de l'art, conduisent à un manque de sécurité et de sûreté dans d'emploi de ce type d'artifice.

Il est remarquable aussi de souligner que la mise en oeuvre traditionnelle de spectacles pyrotechniques standards ou pyromélodiques telle qu'exposée ci dessus est coûteuse tant en produits consommables qu'en main d'oeuvre.
En effet, la mèche sous conduit ,la lance d'allumage,les retards,et l'inflammateur sont détruits à chaque tir. En outre, le fil de liaison n'est en général pas réutilisable, en raison du coût du contrôle et du reconditionnement nécessaire.D'autre part les préparations en atelier des retards à la précision incertaine,leur montage,puis le déploiement sur site,les protections,les liaisons sur place,et la surveillance de l'ensemble nécessitent une main d'oeuvre très importante.

ELFE D'ART a permis de supprimer toutes ces servitudes par l'utilisation,par exemple,d'un allumage par étincelles produit à l'aide d'un circuit électronique intégré DANS l'artifice, à la base de celui-ci.Des liaisons hertziennes sophistiquées gérées par micro ordinateur pilotent ces allumages.

L'initiation nécessite un contact de plots à plots produit uniquement à l'instant où la bombe entre en contact avec le fond du mortier.L'initiation se fait à l'intérieur du réservoir de chasse, au sein de la poudre.(voir schéma)

Ce dispositif présente une SECURITE MAXIMUM étant donné que l'initiation n'est possible qu'au moment du contact, peu de temps avant l'allumage effectif.Dans tous les cas, l'artifice n'est pas susceptible d'être mis à feu. Aucune influence électrique ou électro magnétique.

TRANSMISSION

Dans l'invention nous avons remplacé les commandes électriques habituelles par liaisons filaires par une liaison hetrzienne.

La transmission des ordres se fait en impulsions codées (PCM) et en modulation de fréquence (FM) dans une bande de fréquence définie.
Le choix de la bande de fréquence est fonction des législations en vigueur dans chaque pays utilisateur , de l'environnement radio électrique et des performances recherchées (distances notamment).

L'installation de tir comprend un système de codage et décodage au niveau de la centrale de tir et de chaque satellite .
Les informations sous forme de messages et d'adresses sont codées à l'émission et décodées à la réception.
Le système de codage et décodage de la centrale de tir est constitué par le micro ordinateur de programmation de tir, alors que le système de codage et décodage de chaque satellite est constitué par une carte spécifique à micro processeur.
Les transmissions s'effectuent à travers des liaisons série RS232 et des modems à 1.200 bauds.

Les informations à transmettre sont organisées en messages composés de mots, en utilisant différents formats de mots.
Dans le but d'améliorer la sécurité de transmission en augmentant la redondance on utilise de préférence un format spécifique.
Pour augmenter encore la sécurité on établit les transmissions au moment du tir et non à l'avance.

Des tests sont prévus par le programme, avant et après le chargement des mortiers.

Un numéro de système est attribué à chaque ensemble lors de sa fabrication et inscrit dans la centrale de tir. Ce numéro permet d'accorder l'émetteur récepteur de l'ordinateur avec l'émetteur récepteur de chaque satellite appartenant à un même système.Les satellites sont identifiés par un numéro de code supporté par un bouchon codeur interne fiché sur l'électronique du satellite.
En cas d'échange d'un satellite ou d'un module électronique, il suffit de retirer le bouchon codeur du satellite ou du module à remplacer et de le monter sur le matériel de remplacement.

CENTRALE DE TIR

C'est un Système Informatique Transmetteur d'Ordres (SITO).

Description:
C'est une valise de type "samsonnite" aux dimensions de 46 x 35 x 12 cms d'un poids total de 10 kg qui contient divers éléments.
-Un micro ordinateur portatif doté d'une autonomie interne par batterie rechargeable incorporée.
-Deux lecteurs de disquettes de format 8,9cm (3,5 pouces) sont suffisants pour faire fonctionner le système.
-Un disque dur qui permet un gain de vitesse et offre une capacité de stockage d'informations beaucoup plus importante.

Les programmes sont écrits en basic sous DOS pour une simplification de la composition et de l'utilisation des spectacles grâce à 2 menus principaux.

-Un boîtier électronique associé relié au micro-ordinateur par une liaison série RS 232 contient un MODEM et les émetteurs récepteurs nécessaires à la liaison "Half-duplex" ou bivalente avec les satellites.

-L'alimentation électrique de ce boîtier électronique utilise les batteries de l'ordinateur dont la recharge est assurée par un chargeur monté à demeure.
Le micro-ordinateur,le chargeur,deux interrupteurs (marche et liaison radio encadrent un coupe circuit "coup de poing") le support d'antenne,une prise pour alimentations extérieure, et une sortie pour imprimante sont disposés sur une platine fixée dans la valise de tir de la dimension d'un simple attaché case.

RESULTATS

AVANTAGES:
Facilité de transport et faible encombrement.
Autonomie complète au niveau alimentation électrique.
Montage aisé par simple vissage de l'antenne de transmission.
Verrouillage de l'interrupteur coup de poing par clé interdisant toute utilisation intempestive.
Codage du système.
Utilisations de programmes et de disquettes interchangeables avec disquette spécifique au seul tir si nécessaire.
Ecrans types pour une utilisation aisée sans formation particulière.
Rapidité de mise en place.
Possibilité de modification du rythme de lancement avant ou pendant le tir.
Sécurité MAXIMUM d'utilisation (le tireur est hors du site de tir)
Conduite de tir possible par le client ,le tireur est avec le public ou avec son client pendant le déroulement du spectacle.

CONCLUSION

ELFE D'ART est le résultat de nombreux essais en laboratoire, sur sites expérimentaux, et lors de spectacles officiels.
Il est maintenant démontré que ELFE D'ART offre aujourd'hui un champ de possibilités infinies pour la mise en fonctionnement des artifices de tout types, suivant des séquences ou tout l'art et l'originalité du spectacle pyrotechnique s'exprime, à travers l'imagination de son concepteur.

Ce système exclusif et inédit s'adresse à tous les tireurs de feux d'artifices,mais aussi aux organismes ayant le soucis de créer de nouveaux spectacles par l'exploitation de nouvelles combinaisons de trajectoires, de formes et de couleurs

La visualisation,en deux dimensions des spectacles obtenus grâce à des images de synthèse est rendue possible moyennant l'utilisation d'un outil un peu plus évolué

En résumé il est utile de rappeler que ELFE D'ART est un système perfectionné d'éxécution d'un programme préélaboré d'un spectacle pyrotechnique artistique qui offre de nombreux avantages:

-MAITRISE,PRECISION,SOUPLESSE D'EXECUTION DES TIRS.

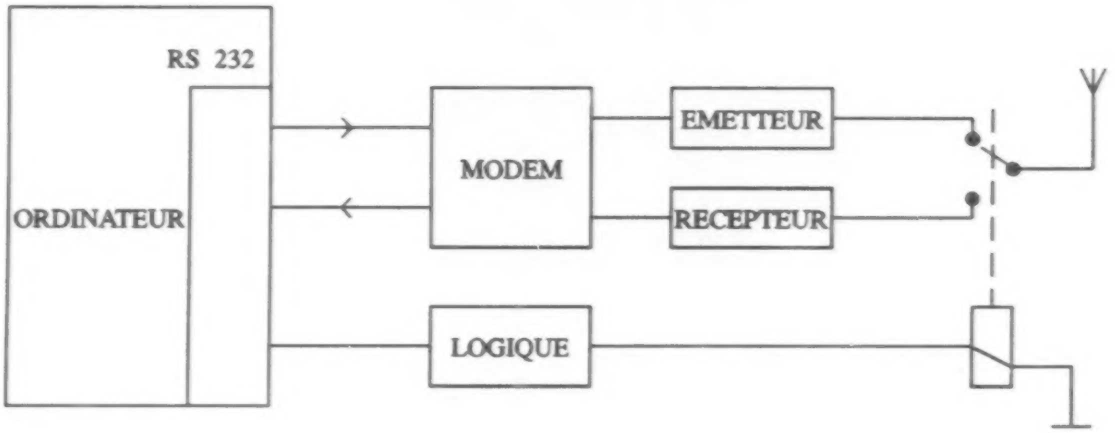
-SECURITE ET SURETE D'EMPLOI EXEPTIONNELLES.

-ECONOMIQUES:TRANSPORTS,MISE EN OEUVRE,MATIERES.

-TECHNOLOGIQUES: PROGRAMMES EVOLUTIFS ADAPTES AUX BESOINS DU CLIENT.

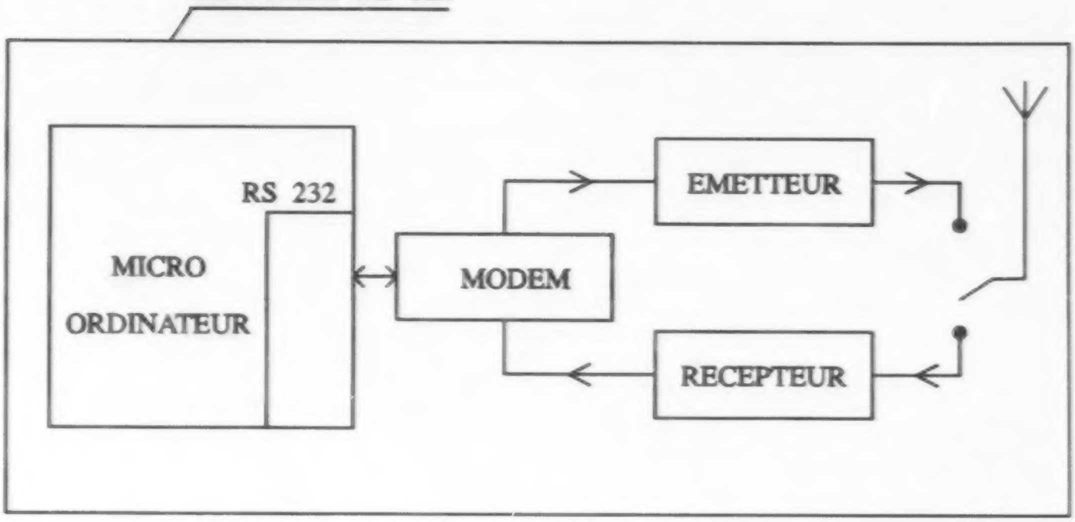
Il suffit d'utiliser ELFE D'ART une fois pour être convaincu que c'est l'outil indispensable à l'artificier moderne.

ANNEXE 1

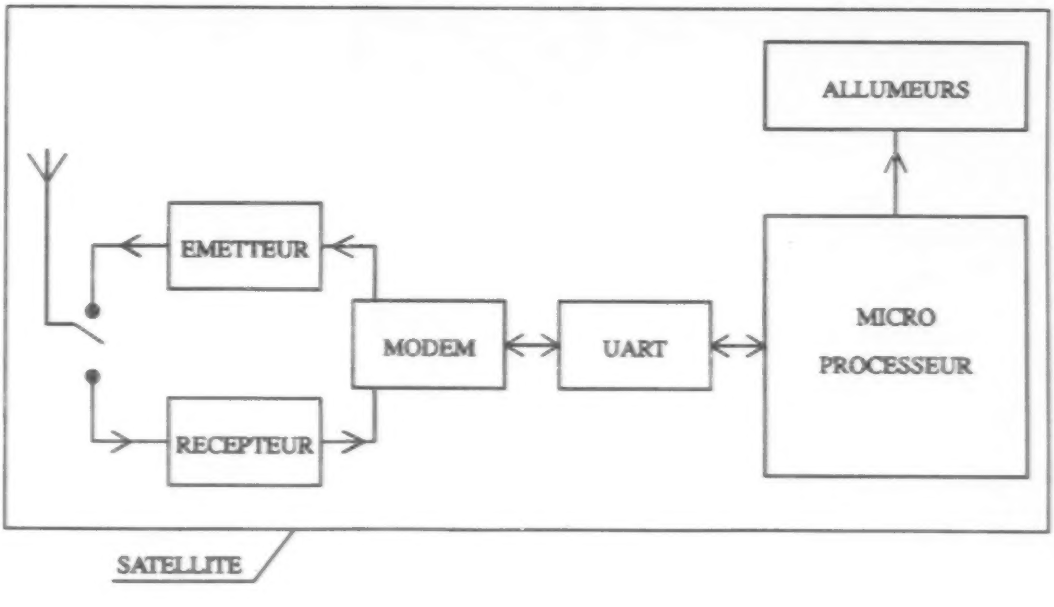

RS 232
ORDINATEUR
MODEM
EMETTEUR
RECEPTEUR
LOGIQUE

CENTRALE - PRINCIPE

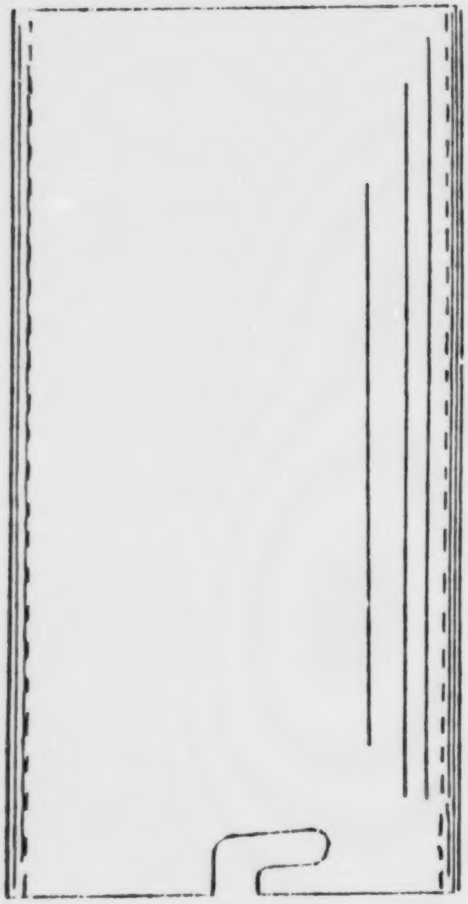
ANNEXE 2


CENTRALE DE TIR
RS 232
MICRO
ORDINATEUR
MODEM
EMETTEUR
RECEPTEUR

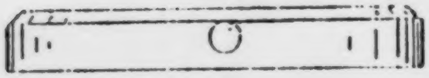
LIASONS HERTZIENNES


ALLUMEURS
EMETTEUR
MODEM
UART
MICRO
PROCESSEUR
RECEPTEUR
SATELLITE

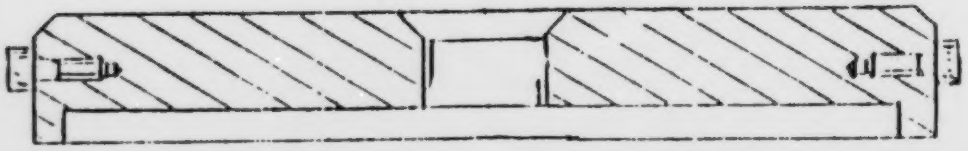
ANNEXE 3



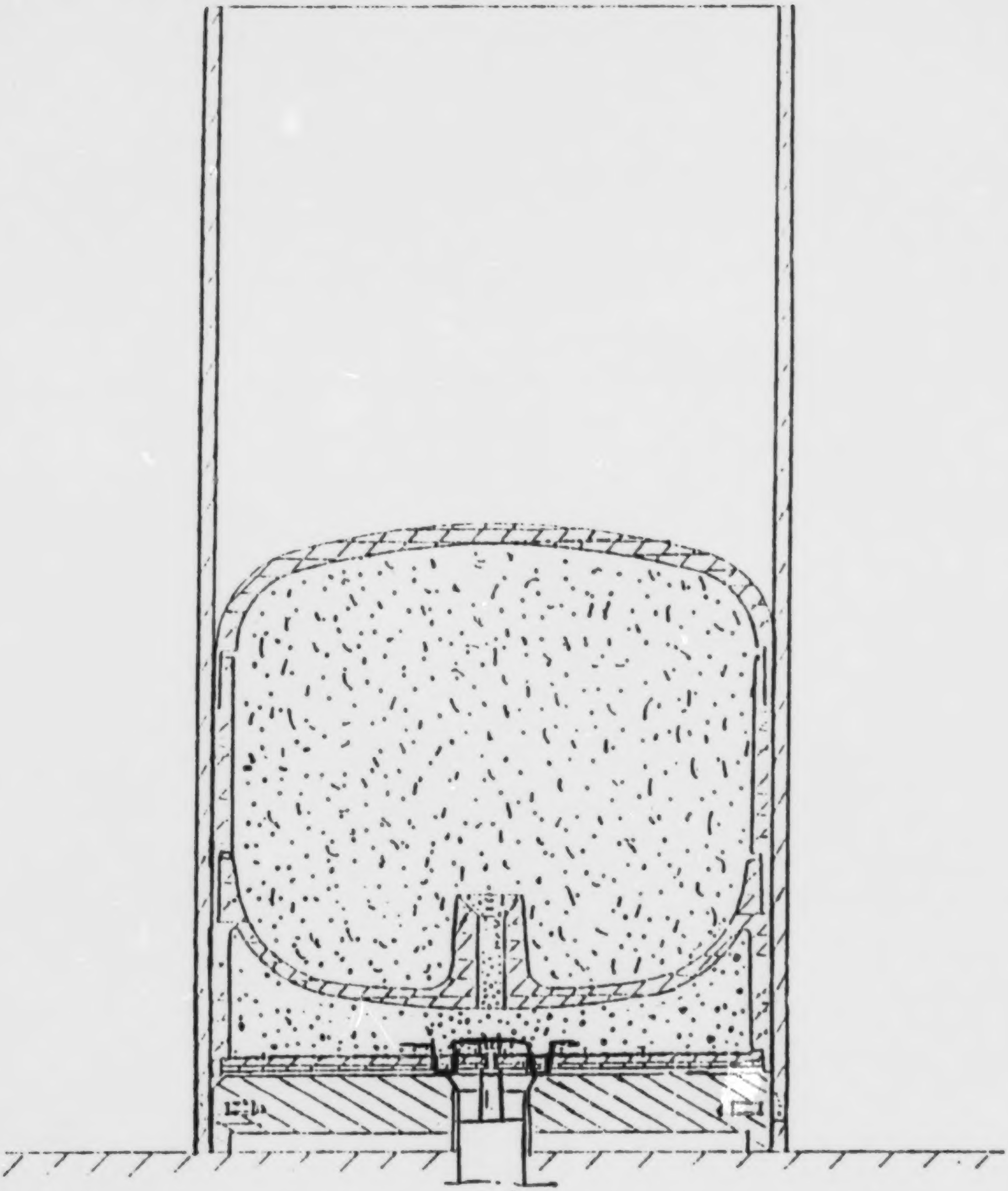
MORTIER



EMBASE

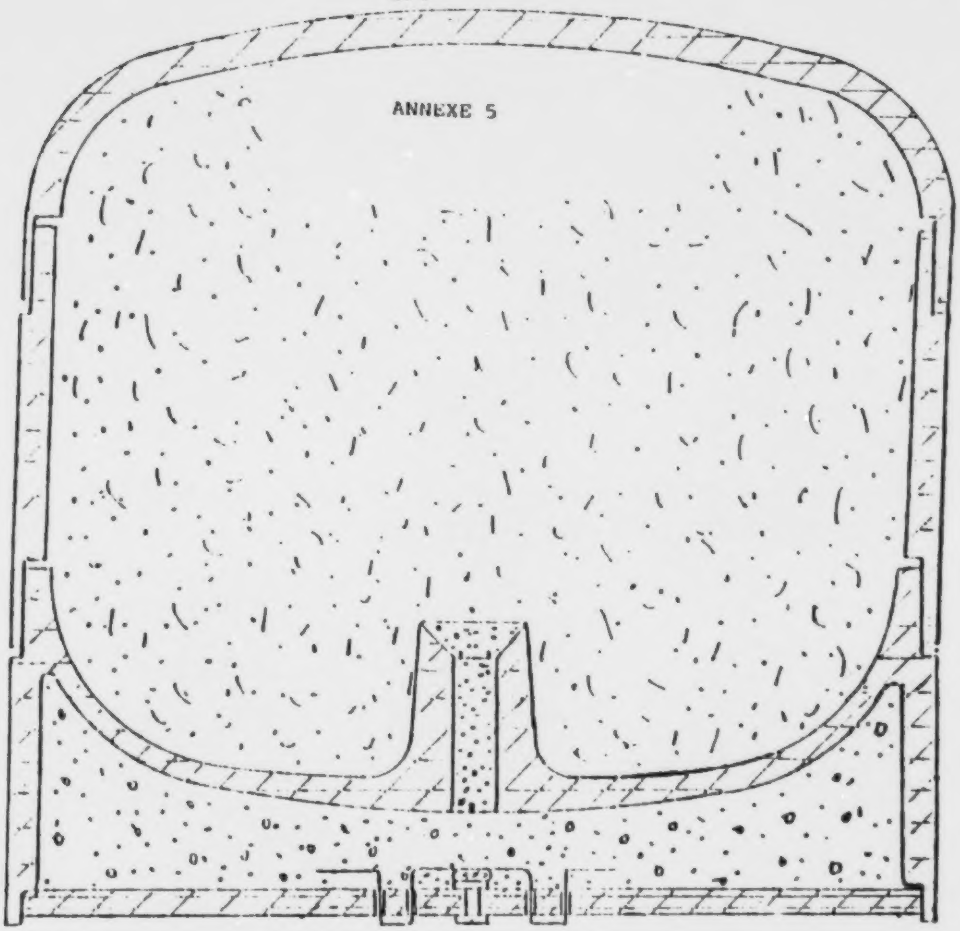


ANNEXE 4

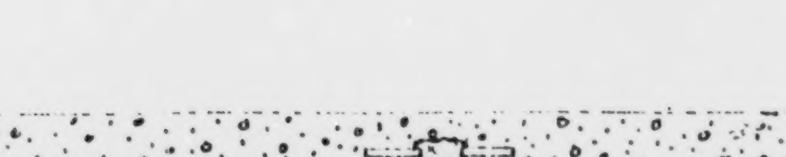


ENSEMBLE MONTE PRET AU TIR

ANNEXE 5



BOMBE EQUIPEE



SYSTEME D'INITIATION

CONTROL OF THEATRICAL PYROTECHNICS IN CANADA

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ABSTRACT

The control of theatrical pyrotechnics in Canada falls under the purview of the Explosives Act and Regulations which is administered by the Explosives Division of the Federal Department of Energy, Mines, and Resources. Areas falling under Federal control include testing and authorization, manufacture, importation, sale, storage, some aspects of transportation by road, as well as blending and use. In some provinces use is controlled to a further degree under provincial legislation.

Although Canadian experience with the use of theatrical explosives has been reasonably good to date, there are still areas that require attention. These include increasing the awareness of basic regulatory and safety requirements within the industry, increasing knowledge of the authorities responsible for approving use, and finally, improving the product performance information that accompanies theatrical explosives.

To achieve these goals will require consultation with industry in an effort to produce a more comprehensive set of regulations governing use. It is hoped to follow this up with a basic safety and regulatory awareness training programme.

LA RÉGLEMENTATION DES PIÈCES PYROTECHNIQUES DE SPECTACLE AU CANADA

RÉSUMÉ

Au Canada, les activités associées aux pièces pyrotechniques de spectacle sont régies par la Loi et le Règlement sur les explosifs, administrés par la Division des explosifs du ministère fédéral de l'Énergie, des Mines et des Ressources. Les aspects relevant de la compétence du gouvernement fédéral sont la mise à l'essai et l'autorisation, la fabrication, l'importation, la vente, l'emmagasinage, certains aspects liés au transport par route, de même que le mélange et l'utilisation. Dans certaines provinces, l'utilisation de ces explosifs est davantage réglementée en vertu de lois provinciales.

Bien que, jusqu'à maintenant, le Canada n'ait pas vraiment connu de mauvaises expériences avec les explosifs de spectacle, certains aspects méritent qu'on s'y attarde encore. Il s'agit de la sensibilisation de l'industrie aux exigences réglementaires fondamentales et aux règlements de base concernant la sécurité, l'accroissement de la connaissance des autorités responsables d'approuver l'utilisation de ce type d'explosif et, enfin, l'amélioration de l'information qui accompagne les explosifs de spectacle sur le rendement de ces produits.

Pour atteindre ces buts, il sera nécessaire de consulter l'industrie en vue de produire une série plus complète de règlements régissant l'utilisation des explosifs de spectacle. On espère pouvoir faire suivre cette initiative d'un programme de formation visant la sensibilisation aux mesures de sécurité et à la réglementation de base.

INTRODUCTION

The Explosives Act came into being on June 12, 1914 and to this day continues to be the federal statute responsible for the nation-wide regulation of the explosives industry. Explosives are defined in general terms as any substance by itself or contained within an article that is manufactured or used with the intention of producing an explosion, detonation, or pyrotechnic effect. In Canada, explosives are viewed as fitting into one of the three broad categories of either blasting explosives and accessories, ammunition and reloading components, or fireworks and pyrotechnic articles. It is quite evident that theatrical pyrotechnic articles and substances fit into the last category. Although several provincial jurisdictions exercise control over some aspects of the use of theatrical pyrotechnics, this paper will deal soley with federal control.

HOW ARE THEATRICAL PYROTECHNICS CURRENTLY CONTROLLED IN CANADA?

The Explosives Regulations made pursuant to the Explosives Act regulate the testing and authorization, manufacture, importation, sale, storage, some aspects of transportation by road, as well as blending and use. Each area of control will be discussed in the sequence presented in this paragraph.

Testing and Authorization

All theatrical explosives commercially available in Canada have been subjected to the authorization process which is detailed in Part II of the Explosives Regulations. This applies to domestically produced products as well as those of foreign manufacture. In Canada, the Explosives Division is responsible for classifying explosives for the purposes of both the Explosives Act as well as the Transportation of Dangerous Goods Act. Laboratory test work is conducted on our behalf at the Canadian Explosives Research Laboratory in Bells Corners which is located on the western outskirts of Ottawa. There are occasions with respect to foreign products where test work is waived when the manufacturer's submission is accompanied by a recognized competent authority approval document. In short, the authorization process is intended to ensure that the product is safe to transport, store, use, and for domestic purposes only, manufacture. The classification process is intended to classify, according to the United Nations Classification system, those explosives products which have qualified for authorization. Also included in this process is assignment to Class 7 Division 2 Subdivision 5 ,(7.2.5), the appropriate Canadian classification code for theatrical pyrotechnics.

Manufacture

Manufacture of theatrical pyrotechnics in Canada must be covered by a factory licence issued pursuant to Part IV of the Explosives Regulations. There are only two companies in Canada that manufacture theatrical explosives.

Importation

The importation of any quantity of authorized theatrical pyrotechnics must be covered by an Explosives Importation Permit issued by the Explosives Division pursuant to Part XIV of the Explosives Regulations. General importation permits are valid for one importation during a twelve month period while annual importation permits are valid for an unlimited number of importations during a twelve month period. The current fees for such permits are $25 and $65 respectively.

Special general importation permits may be issued to qualified individuals or companies for products not yet authorized that are required for evaluation or for other special purpose. If there is a continued requirement or commercial interest in further importation, full authorization is required. Such importation permits are issued on a case by case basis.

Sale

The sale of theatrical pyrotechnics is controlled by Part X of the Explosives Regulations. Storage of any quantity for sale must be covered by a fireworks magazine licence issued by the Explosives Division. Vendors may only sell theatrical pyrotechnics to those in the occupation for which these explosives were intended.

Storage

The storage of theatrical pyrotechnics for private use and not for sale is controlled by Part XI of the Explosives Regulations. Up to 25 kilograms gross weight may be stored without a fireworks magazine licence in a lockable container within a building that in itself is not adapted for the storage of explosives. Up to 125 kilograms gross weight may be stored in a detached store or warehouse dedicated to the storage of fireworks and located a safe distance away from vulnerable features such as public roads and dwellings. Storage in excess of these quantities requires a fireworks magazine licence.

Transportation

Safety requirements associated with the handling and transportation by road of theatrical pyrotechnics is covered by Part VI of the Explosives Regulations.

The responsibility for regulating packaging standards, safety marks, documentation, and training falls under the Transportation of Dangerous Goods Regulations.

Blending and Use

Authority to blend and use two-component theatrical explosives as well as the pre-manufactured variety is restricted by Part XVI of the Explosives Regulations to technicians or people working under the direct supervision of a technician.

A technician is defined as person qualified to use theatrical explosives by reason of their knowledge, training, and experience.

Two-component theatrical pyrotechnics may be blended and used subject to the following conditions:

1. Blending and use must be done by a technician or under the direct supervision of a technician.
2. Manufacturer's directions must be followed paying close attention to safety distances from the effect to vulnerable features as well as recommendations on the nature of associated equipment, eg. flash pots, that should be used.
3. Two-component materials must be securely stored until needed when at that time only the minimum amount is blended and deployed.
4. Surplus blended product must be destroyed or safely disposed of.
5. Technicians must take reasonable precautions to prevent accidents as well as unauthorized people gaining access to either mixed or unmixed two-component theatrical pyrotechnics.

What Has Been The Canadian Experience?

Although experience in Canada with theatrical pyrotechnics has been reasonably good, several incidents over the years indicate that there is room for improvement.

1. A hotel patron receives minor burns to one hand when a loaded flash pot located on stage near the dance floor is mistaken for an ashtray.
2. A licensed vendor called to express that he may have made an error in judgement in selling theatrical pyrotechnics to an individual who he later felt might be mentally unstable.
3. A technician's assistant received second degree burns to her hands, face, and neck when she manually lit, (with a lighter), what she thought was smoke composition. Pre-mixed two-component smoke composition had been manually lit on set all that day without incident. When the supply had been exhausted, a local theatrical pyrotechnics dealer supplied pre-mixed flashpowder as a "reasonable substitute". The assistant, unaware of the properties of flashpowder, suffered the consequences of a number of unsafe practices and bad judgement.
4. Attendees at a New Year's Eve dinner/dance in a small hotel banquet room "saw red" when theatrical smoke generators intended to enhance the ambience of the dance floor stained clothing, caused nausea, vomiting, nasal discharge, and other feelings of ill health. Another complicating factor is that two women in attendance were unknowingly 1 1/2 months pregnant and by consequence have health concerns about their unborn.

The technician in question clearly created too much smoke for the size and ventilation capacity of the room in question.

What Changes Are Needed?

Improvements in education and communication in the special effects community as well as the authorities giving approval for use will go a long way in helping to prevent incidents. The following needs have been identified:

1. Steps must be taken to ensure that all people in the theatrical effects business community, which includes tv and movie production as well as live entertainment, are aware of the basic rules, regulations, and good safety practices governing their work. Authorities having jurisdiction over locations where pyrotechnic effects are used are included in this group as well.
2. A means of identifying competent technicians and their degree of experience and proficiency must be established.
3. Safety and performance information describing the position, nature, duration, and magnitude of the effects to be used must be made available to the authority having jurisdiction over the location where they are to be used.

How Do We Get There?

Regulatory change is achieved by following the regulatory process. This process includes:

1. Informal dialogue with industry and other interested parties. The creation of a nation-wide special effects technicians' association which is truly representative of tv/movie production interests as well as those of live entertainment would of great benefit.
2. The drafting of the proposed legislation.
3. Making industry aware of such proposed legislation by pre-publishing the text in Part I of the Canada Gazette. In addition to this, a synopsis of proposed changes would be published in the Explosives and Pyrotechnics Newsletter, a CANMET publication. This periodical receives wide distribution to the explosives and pyro community in Canada roughly three times a year.
4. Addressing all feedback to produce a final set of regulations that best satisfies the safety concerns of industry and public as a whole.
5. Publishing the final set of regulations in Part II of the Canada Gazette as law. The final set of regulations would again be reviewed in the Explosives and Pyrotechnics Newsletter.

Once the new set of regulations are in place, some form of awareness training will be required. This will most certainly include information products such as brochures and could extend to staging several seminars at selected locations across Canada.

HAZARD MANAGEMENT FOR THE MANUFACTURE OF PYROTECHNICS IN GERMANY

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ABSTRACT

The presentation describes how legislation and the safety rules of the Industrial Injuries Insurance Institutes organize a system of safety measures with the aim of minimizing the number as well as the severity of accidents in the German pyrotechnic industry.

The safety rules for the manufacture of pyrotechnics classify pyrotechnic compositions as well as articles including semi-finished products into five hazard groups. This classification is normally done by the manufacturer himself on the basis of descriptive terms such as violent/fast/slow or very sensitive/sensitive/low sensitive characterizing burning behaviour and sensitivity, only supported by some exemplarily assignments of well-known pyrotechnic compositions and articles. By these groups the quantity and personnel limits for rooms and buildings are set, primarily depending on the type of process. Within this system, there are only three different safety distances depending on type and orientation of the buildings.

Earlier in BAM, a system of quantifying the degree of hazard of pyrotechnic compositions by a hazard number has been developed, based on safety characteristic data representing their thermal sensitivity, mechanical sensitivity and sensitivity against detonation shock. This hazard number can be used to classify pyrotechnic compositions into the hazard groups described above. The presentation concludes with relating typical ranges of some safety characteristic data directly to the aforesaid descriptive terms characterizing the sensitivity of pyrotechnic compositions.

INTRODUCTION

Pyrotechnic compositions are usually sensitive, but frequently also effective explosive substances. A certain number of incidents and accidents with pyrotechnic compositions seems to be unavoidable. Hazard or safety management in pyrotechnic industry should therefore aim to reduce the probability of accidental ignitions as well as the resulting damage.

In Germany, a complex system of legislative measures exists to ensure a reasonable safety level for all branches of explosives industry. Basis is a licence according to the Federal Immission Control Law (1) which is mandatory for the manufacture of explosives and pyrotechnics as well. This licence is granted by the competent authority (e.g. the factory inspectorate) provided that there are no reasons for refusal, i.e. that the manufacturing facilities and the operations comply with the relevant regulations and safety rules.

In addition to general provisions for environmental and industrial safety, there are specific provisons for the explosives industry. The storage of explosives such as blasting agents, ignitors or initiators, propellants and pyrotechnics is subject to the Second Regulation to the Explosives Law - 2. SprengV - (2) and based on the classification into four storage groups which are equivalent to the divisions 1.1 to 1.4 of the UN Recommendations on the Transport of Dangerous Goods (3). Safety distances required by this Regulation depend on the storage group and quantity of the explosives to be stored as well as on the construction of the magazines and the type and construction of endangered buildings and places. Some figures are given in table 1.

For the manufacturing and processing of explosives and for other connected operations excluding storage the safety rules of the Industrial Injuries Insurance Institutes (Berufsgenossenschaft) of the chemical industry apply. The "Safety rules on explosives and explosive articles - general rules" - VBG 55 a - (4) are applicable to all types of explosives. They deal with general definitions, construction and equipment, inspection and operative measures including training, quantity and personnel limits, servicing, protective clothing, etc. Figure 1 shows the different permissible constructions of buildings. The required interior safety distances between dangerous buildings (buildings in which explosives are present) and other buildings and places including dangerous ones are equivalent to the interior distances specified in the above mentioned storage regulation 2. SprengV.

In addition to the general rules, there are special "Safety rules on the manufacture of pyrotechnic articles" - VBG 55 k - (5). The content of these safety rules, the particular classification system used in these safety rules, and some experience from research work related to this classification system are object of this paper.

SAFETY RULES ON THE MANUFACTURE OF PYROTECHNIC ARTICLES

The "Safety rules on the manufacture of pyrotechnic articles" - VBG 55 k - apply to all parts of a plant in which pyrotechnic compositions or articles are manufactured or processed, or therewith connected are transported or stored, so far as the storage is not subject to the 2. SprengV.

Other operations as testing and disposing are regulated by the general safety rules VBG 55 a. Both safety rules VBG 55 a and 55 k are applicable to the storage (long-term as well as short-term) of pyrotechnic ammunition, which in Germany is not subject to the Explosives Law (6), but to the Weapons Law (7). But, for the purposes of the above safety rules, the term pyrotechnic article includes also the pyrotechnic ammunition.

The main provisions of the VBG 55 k deal with hazard classification, distances between buildings, and quantity or personnel limits. For a number of different operations separate buildings are required, but these buildings may consist of several rooms for equivalent operations. Other operations, but also certain groups of chemicals require separate rooms. Furthermore, some substances are prohibited as components of pyrotechnic compositions, other substances only in certain mixtures. Details are described in the following. The VBG 55 k includes also particular provisions for the manufacture of some types of firework, e.g. throw downs, table bombs, caps, sparklers. Those particular provisions are not presented here.

Separate Buildings

The following operations require separate buildings:

- storage and preparation of non-explosive chemicals,
- manufacturing of compositions by machine,
- manufacturing of compositions by hands and processing (granulating, forming of dragées and pellets, priming, sieving),
- drying of compositions, semi-finished products and articles,
- short-term storage of compositions,
- processing and assembling of compositions and semi-finished products,
- short-term storage of semi-finished products and articles,
- storage of articles.

Deviating from the above, short-term storage (intermediate storage) is permitted in separated rooms of working buildings if the partition walls are sufficiently pressure resistant.

Separate Rooms

The following processes on pyrotechnic compositions are not allowed to be carried out simultaneously in the same room:

- granulating,
- forming of pellets,
- sieving,
- filling in of loose or open compositions,
- extruding or casting,
- compacting of compositions (shaking, ramming, pressing),
- grinding,

- filling and sealing of semi-finished products,
- processing of the cases of semi-finished products (e.g. flanging, cutting),
- laquering of shaped or pressed bodies,
- priming of semi-finished products,
- short-term storage of compositions and semi-finished products.

Assembling and finishing operations which must not be carried out at the same time in one room are:

- assembling or inserting of semi-finished products,
- sealing of assembled and inserted semi-finished products,
- priming of semi-finished products,
- operations as attaching sticks or fins, glueing on, etc.,
- laquering and drying of finished articles,
- imprinting or labelling of articles with open fuse,
- packaging of articles,
- covering of packages (e.g. paraffining, pasting with paper or foil).

Chemicals which require separated rooms for storage and preparation processes as grinding, sieving and drying are:

- chlorates and perchlorates,
- ammonium perchlorate,
- nitrates, peroxides and other oxidizers,
- light metals,
- other reducing agents and additives (e.g. antimony sulphides, milk-sugar, dyes, charcoal, resins, carbonates, oxalates),
- inflammable liquids,
- red phosphorus,
- cellulose nitrates (e.g. collodion cotton).

The aim of all these separating provisions is either to avoid the accidental formation of dangerous mixtures, or to separate areas of different accident probabilities. The latter enables to adjust the permitted quantities of pyrotechnic compositions in accordance with the ignition probabilty, and to establish an acceptable and passably uniform risk (i.e. the ignition probability multiplied by the possible damage) for the different manufacturing processes and areas.

Prohibited Components and Mixtures

In order to avoid risks from unnecessary sensitive, effective or unstable pyrotechnic compositions the following components and mixtures are prohibited:

- sulphur with free acid or with more than 0,1 % of incombustible components,
- flowers of sulphur,
- acid laquers, binders and the like,
- potassium chlorate with more than 0,15 % of bromate,
- light metals with more than 0,25 % of added unsaturated fats and oils,

- white (yellow) phosphorus,
- chlorates in mixture with metals, antimony sulphides, hexacyanoferrates,
- chlorates in mixtures with ammonium salts (exept for mixtures of ammonium chloride and potassium chlorate).

Hazard Classification

The employer shall assign pyrotechnic compositions, semi-finished products and articles to one of five groups according to their burning velocity and their mechanical or thermal sensitivity. The full descriptions of these groups are given in table 2. Descriptive terms like "very violent burning", "violent burning", "fast burning", etc. are used to characterize the respective behaviour.

Since there are neither test methods agreed nor criteria which differentiate between these graduated descriptive terms, for orientation, exemplarily assignments of a number of well-known pyrotechnic compositions, semi-finished products and articles are given in an annex to the VBG 55 k. Some examples for the different groups are listed in table 3. However, explanatorily to these examples it is emphasized that neither the name of a pyrotechnic mixture nor its chemical composition is sufficient for a proper classification. A pyrotechnic composition may change its properties during manufacturing and processing, and the burning behaviour of both compositions and articles may strongly depend on arrangement and packaging.

Quantity and Personnel Limits

The general safety rules VBG 55 a require that in rooms or buildings or on places the quantity of explosives and the number of persons shall be the minimum necessary for the progress of work, but no more than the permitted ones. For the manufacture of pyrotechnics, these quantity and personnel limits are set by the VBG 55 k in great detail. Table 4 specifies the limits for the manufacturing and processing of compositions, table 5 for semi-finished products and articles.

In case there are compositions or articles of different groups in one room or building, the permissible quantities are to be determined according to the following rule: The sum of the actual quantities of the different groups as percentages of the respective maximum quantities shall not exceed 100, for example: Table 4, no II A, 1a "Filling by hand"

Group 1	0,3 kg = 60 %
Group 2	0,3 kg = 20 %
Group 3	2,0 kg = 20 %

This scheme of setting maximum quantities of compositions and maximum numbers of persons is of special use in the pyrotechnic industry. Since the articles produced change frequently, it is not possible to adjust the safety distances to a particular manufacturing process. On the contrary, the dangerousness of the different processes has to be fitted to the existing conditions (distances, construction of buildings) - for instance by means of quantity limits as described above. In this connection, dangerousness is understood in terms of

- the explosive effect which is to be expected in case of an accident, as well as
- the sensitivity of the pyrotechnic compositions involved, and
- the ignition risk given by the particular process.

Safety Distances

For the said reasons, deviating from the general safety rules VBG 55 a the special provisions of the VBG 55 k distinguish for the manufacture of pyrotechnics between only three different safety distances:

- 15 m: dangerous buildings to dangerous or other buildings (doors, windows and venting walls shall not be directed to each other),
- 25 m: venting walls to venting walls or to other buildings in venting direction,
- 30 m: dangerous buildings to other buildings in which a larger number of persons regularly stays.

The safety distances of the general safety rules VBG 55 a apply to long-term storage of pyrotechnics as far as the storage is not subject to the 2. SprengV; they also apply to drying buildings.

HAZARD CLASSIFICATION BY HAZARD NUMBERS BASED ON SAFETY CHARACTERISTIC DATA

As already mentioned, primarily the employer himself is responsible for the assignment of compositions and articles to one of the five groups of the VBG 55 k, but there are no agreed test methods he can use. In case of doubts, the "Berufsgenossenschaft" decides after having asked a competent institute which is BAM for not exclusively militarily used pyrotechnics.

For the classification of pyrotechnic compositions according to the VBG 55 k, BAM has been using a more quantitative system since many years (8,9). This system is based on safety characteristic data as usually determined at BAM for all types of explosive substances. The single test results are rated by certain, standardized numbers of points, the sum of which gives a hazard number as a measure of the overall hazard of an explosive substance. Afterwards, in several other countries more or less similar systems for assessing the degree of hazard of explosive substances have been developed (10-15).

Safety Characteristic Data of Explosive Substances

The safety characteristic data as determined by BAM, using the test methods described in (16), are grouped into three different sensitivities:

- sensitivity to thermal stress
    - ignition temperature
    - ignitability by sparks, black powder fuse, gas flame and red-hot steel rod
    - combustion time in a red-hot steel bowl
    - limiting diameter in the Koenen test

- sensitivity to mechanical stress
    - sensitivity to friction
    - sensitivity to impact
- sensitivity to detonation shock
    - lead block expansion
    - behaviour in steel tubes

Some of these methods are included into the UN Tests and Criteria Manual (17), namely the Koenen test 1 (b) (i), the friction test 3 (b) (i), the impact test 3 (a) (ii), and the 2" steel tube test 1 (a) (i).

Hazard Numbers

Table 6 shows the maximum numbers of points allotted to the different safety characteristic data. Details are given in (9). These points are summed up to the respective values of sensitivity k, with 100 points maximum each. The sum of these three values of sensitivity is the number of total hazard G (the hazard number):

$$G = k_{th} + k_{m} + k_{d}$$

Therefore, the maximum hazard number is G = 300. For the sake of completeness, it should be mentionened that an index T, M or D at the hazard number indicates that the respective sensitivity exceeds 50 points ($G = 187_{TM}$ for instance).

A single hazard number facilitates the comparison of different explosive substances/ pyrotechnic compositions, and it is a useful help to explain the degree of hazard of an explosive substance to a non-specialist. On the other hand, the reduction of the different safety characteristic data to a single number results in [illegible] loss of information. Furthermore, the dangerousness of some pyrotechnic compositions, especially "gasless" compositions with relatively low heats of reaction and melting points of the reaction products (e.g. barium peroxide-metal-compositions) is not sufficiently represented by the usual safety characteristic data and the hazard number, respectively.

Relation between Hazard Number and Hazard Groups

Considering the above reservations, a numerical relation between the hazard groups for pyrotechnic compositions according to VBG 55 k and hazard numbers based on safety characteristic data has not been published before having gained sufficient experience with such a classification system. A relation which has been proved to be useful is given in table 7 (18). Classifying pyrotechnic compositions in this way is undoubtedly more reliable than using only verbal descriptions or exemplarily assignments as those in tables 2 and 3.

Relating Safety Characteristic Data to Hazard Groups

After having classified a large number of pyrotechnic compositions by means of the above relation, as detailed in table 8, it was looked into the distribution of the single safety characteristic data within the different hazard groups (19). Figure 2 shows the distribution of the ignition temperature determined in a Wood's metal bath, as an example.

According to the definitions of the hazard groups for pyrotechnic composition by descriptive terms (compare table 2), compositions of group 1 should be very sensitive against frictional stresses, those of groups 2 and 3 should be sensitive, and those of group 5 should be low sensitive. Taking into account common experience with the sensitivity of pyrotechnic compositions and usual hazards during their manufacture and processing, typical ranges of safety characteristic data can be related to the descriptive terms as shown in table 9 for the ignition temperature, friction sensitivity and impact sensitivity. Or in other words, at least for the purposes of the safety rules VBG 55 k the question "How sensitive is very sensitive" can be answered.

SUMMARY

In the Federal Republic of Germany, the pyrotechnic industry is subject to a system of legislative measures with which the necessary level of industrial and environmental protection shall be ensured. The most specific provisions are those of the "Safety rules on the manufacture of pyrotechnics" of the Industrial Injuries Insurance Institutes.

The system of classifying pyrotechnic compositions as well as articles or semi-finished products, which is used in these safety rules, considers not only explosive properties as pressure and thermal effects or fragments, but also the mechanical and thermal sensitivity, the ability to explode under more or less strong confinement, or the burning or propagation rate. However, the different hazard groups are characterized by only verbal descriptions of these properties and not by tests with respective criteria. Quantity and personnel limits are based on this classification and of the type of process as well.

BAM uses another system for classifying pyrotechnic compositions to the same hazard groups based on safety characteristic data from which a hazard number is derived. This system was described and discussed. The descriptive terms used in the safety rules for characterizing the burning behaviour and the sensitivity of pyrotechnic compositions of the different hazard groups can be related directly to typical ranges of some safety characteristic data by means of the classification by hazard numbers.

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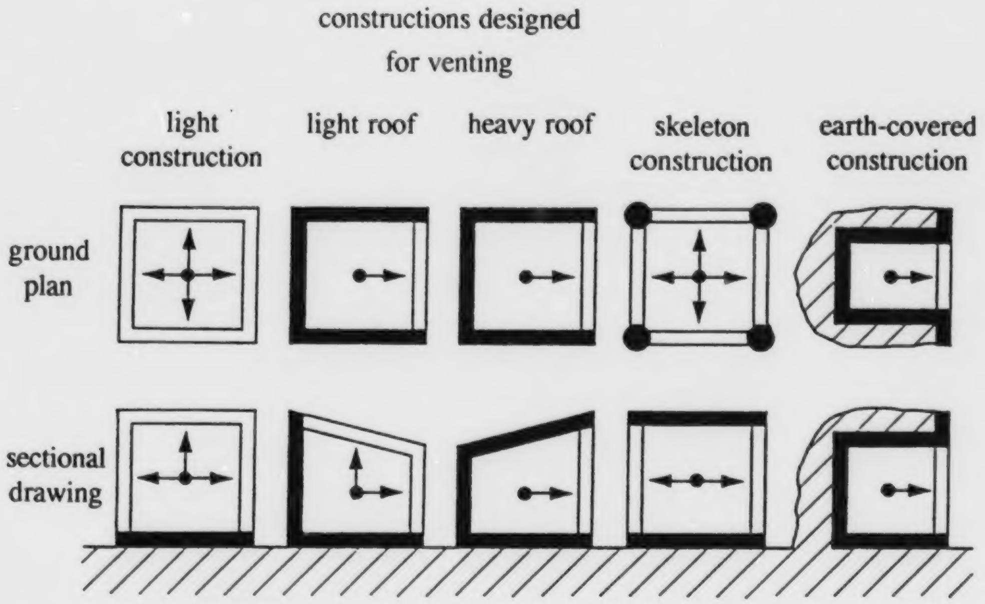
constructions designed
for venting
light construction
light roof
heavy roof
skeleton construction
earth-covered construction
ground plan
sectional drawing

Figure 1: Constructions of buildings in the explosives industry

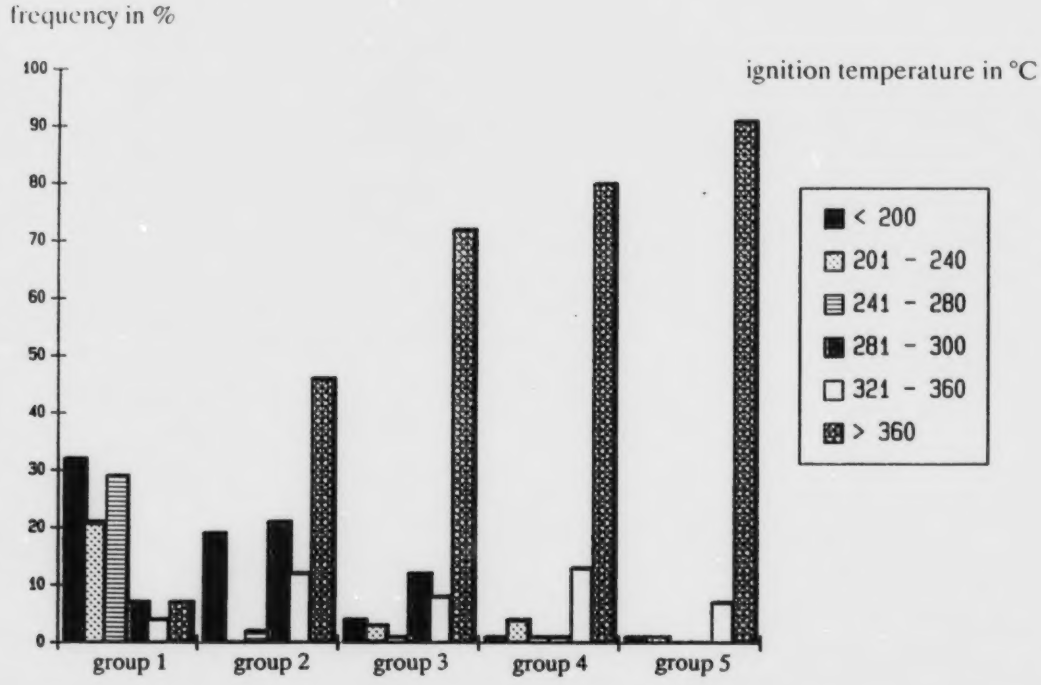

Figure 2: Distribution of ignition temperatures within the hazard groups for pyrotechnic compositions

Table 1: Safety distances for explosives magazines

storage group	safety distances in metres		
	inhabited areas	public traffic routes	factory-owned buildings
1.1	$22 \cdot M^{1/3}$	$15 \cdot M^{1/3}$	$0{,}8 \ldots 8{,}0 \cdot M^{1/3}$, (partly 30)
1.1*	$22 \cdot M^{1/3}$, (275)	$15 \cdot M^{1/3}$, (180)	$0{,}8 \ldots 8{,}0 \cdot M^{1/3}$, (partly 40…275)
1.2	$58 \cdot M^{1/6}$, (90)	$39 \cdot M^{1/6}$, (60)	(0…90)
1.2*	$76 \cdot M^{1/6}$, (135)	$51 \cdot M^{1/6}$, (90)	(0…135)
1.3	$6{,}4 \cdot M^{1/3}$, (60)	$4{,}3 \cdot M^{1/3}$, (40)	$1{,}0 \ldots 6{,}4 \cdot M^{1/3}$ with (10…60), or (0…10)
1.4	(25)	(25)	(10)

*: danger of severe fragments
M: net explosive mass in kg
(): minimum distances

Table 2: Hazard groups of the safety rules VBG 55 k

Pyrotechnic compositions	Semi-finished products and articles
Group 1	
Compositions of this group burn very violently. Even without confinement small quantities are able to explode. They are mechanically and thermally very sensitive. Their dangerousness results from pressure and flame effects.	Articles of this group are capable of mass explosion. The surroundings are endangered by pressure effects (shock waves), flame effects, debris and fragments.
Group 2	
Compositions of this group burn violently. Under confinement (also self-confinement of small quantities) they are able to explode. Their burnung rate strongly increases with self-confinement. The compositions are mechanically and thermally sensitive. Their dangerousness results from pressure and flame effects.	Articles of this group are not capable of mass explosion. After ignition these articles first burn and explode one by one. In the course of a fire the number of simultaneously exploding articles increases. Projected articles are able to propagate fires and explosions and to explode upon impact. Fragments can be produced. The surroundings are endangered by fragments, firebrands and weak pressure effects.
Group 3	
Compositions of this group burn fast. Under confinement they are able to explode or deflagrate. Their burning rate changes only slightly when the quantity is increased. The compositions are mechanically and thermally sensitive. Their dangerousness results mainly from flame effects.	Articles of this group burn very violently and with strong evolution of heat. The fire propagates quickly to all the articles. Articles can be projected burningly. Single articles can explode. The surroundings are mainly endangered by flames, radiation heat and firebrands.
Group 4	
Compositions of this group burn with low to medium velocity. Their burning rate normally do not increase with increasing quantity. Under confinement the compositions can also deflagrate. They are of different mechanical and thermal sensitivity. Their dangerousness results mainly from flame or heat effects.	Articles of this group burn one by one. They can singly explode. The propagation rate of the fire is low. The surroundings can be endangered by firebrands.
Group 5	
Compositions of this group burn slowly. They are thermally and mechanically low sensitive. The surroundings are not endangered.	Articles of this group can singly burn or explode. The fire or burning is reduced to the single article or the content of the package. The surroundings are not endangered.

Table 3: Exemplarily assignments to the hazard groups of the safety rules VBG 55 k

Pyrotechnic compositions	Semi-finished products and articles
Group 1	
- perchlorate-metal report compositions - chlorate report compositions - chlorate or perchlorate whistling compositions - cellulose nitrates, dry, non-gelatinized - barium peroxide-zirconium compositions	- flash shells (maroons) - casings containing flash compositions, also sealed - anti-hail rockets
Group 2	
- nitrate-metal-sulphur compositions - compositions with more than 65 % of chlorates - black powder - nitrate-boron compositions	- large firework shells, fuse unprotected - signal flares, non-pressed - report bullets (bird scarers), unpacked - report cartridges, unpacked - black matches, uncovered
Group 3	
- nitrate-metal compositions without sulphur - compositions with up to 65 % of chlorates - compositions with black powder - lead oxide-silicon with more than 60 % of lead oxides - perchlorate-metal compositions, but others than report compositions	- large firework shells, fuse protected - signal flares, pressed - report cartridges in primary packages - quick matches in transport packages - waterfalls - vulcanos, silver wheels - black powder delays
Group 4	
- coloured smoke compositions - white smoke compositions, exept those named in group 5 - compositions with less than 35 % of chlorate - pesticide compositions based on aluminium-phosphorus	- large firework shells, without flash compositions, in transport packages - signal ammunition, without flash compositions, up to 40 g of composition - small fireworks, fuse unprotected, exept vulcanos, silver wheels - black powder delays, packed
Group 5	
- slow-burning heating compositions - white smoke compositions based on hexachloroethane, with zinc, zinc oxide and less than 5 % of aluminium or 10 % of calcium-silicon	- small fireworks in primary packages - signal ammunition in transport packages - delays without black powder - coloured smoke devices, sealed - table bombs, unpacked - white smoke devices (comp. see group 5)

Table 4: Maximum number of persons and quantity of compositions in kilogram

Rooms and buildings	Number of persons	Group 1 quantity	Group 2 quantity	Group 3 quantity	Group 4 quantity	Group 5 quantity
I. Rooms for the manufacturing (mixing and processing) of compositions						
A. Mixing by hand						
1. mixing buildings with several mixing rooms per room	1	-	1,0 2,5**	5,0	10	10
2. mixing buildings with only one mixing room per room	1	-	1,0 2,5**	10	20	20
B. Mixing by machine (remotely operated)						
1. for all approved building designs						
a) rooms not devides into cells per room	0	1,0	5,0	10	50	125
per building	0	5,0	25	*	*	*
b) rooms devided into cells per cell	0	0,5	2,5	5,0	25	25
per room	0	5,0	12,5	25	125	125
per building	0	10,0	25	*	*	*
2. Emptying of mixing drums group 1	1	1,0				
group 2	1		5,0			
group 3	1			10		
group 4	2				50	
group 5	2					125
C. Granulating, forming of dragées and pellets (moist)						
1. by hand (also cutting)	1	0,25	2,0	5,0	10	10
2. by machine	1	0	0	60	100	100
3. by remotely operated machine	0	1,0	20	60	100	100
D. Coating, priming						
1. by hand	1	0,25	2,0	5,0	10	10
2. by machine	1	0	0	70	100	100
3. by remotely operated machine	0	1,0	20	70	100	100
E. Sieving of compositions processed according to C						
1. by hand	1	0	2,0	5,0	10	10
2. by machine	1	0	0	0	50	50
3. by remotely operated machine	0	1,0	20	70	100	100
F. Intermediate storage of compositions in vented buildings						
1. in rooms of intermediate storage buildings	0	5,0****	20 50***	60	100	3000
2. in rooms between working rooms	0	2,5****	10 25***	30	50	3000
3. in rooms at the end of working buildings	0	5,0****	20 50***	60	100	3000

* Quantity not limited, if propagation from room to room not possible
** Black powder
*** Black powder in transport packaging
**** This quantity applies also to Xylokoll® (nitrated saw dust)

Rooms and buildings	Number of persons according to group					Group 1 quantity	Group 2 quantity	Group 3 quantity	Group 4 quantity	Group 5 quantity
	1	2	3	4	5					
II. Rooms for the processing of compositions to semi-finished products										
A. Filling										
1a by hand	1	3	3	3	as needed	0,5	1,5	10	30	500
1b black powder by hand		2					2,5**			
2. by machine	1	max. 3				0,25	0,5	5,0	30	500
3. by remotely operated machine	0	0	0	0		1,0	5,0	20	100	500
B. Loading of dosing equipments	1	1	1	1		1,0	5,0	20	100	500
C. Compacting (shaking, ramming, pressing)										
1. by hand	0	max. 2				0	0,5	1,0	30	50
2. by machine	0	max. 2				0	0,5	1,0	30	500
3. by remotely operated machine	0	0	0	0		1,0*	5,0*	20*	100*	500*

* Quantity in the process room, not in the control room
** In primary packagings 4 kg

Table 5: Maximum number of persons and quantity of semi-finished products and articles (quantities are net masses of composition in kilogram)

a) in working rooms b) in packaging rooms c) in intermediate storage rooms

Group	Type of room	Quantity in kg	Number of persons	Special cases
1	a	3,0	1	Only up to 2 kg, if the single article contains more than 20 g.
	a	1,5	2	
	b	15	1	
	c	15	0	Only up to 5 kg, if the single article contains more than 20 g.
2	a	10	2	Uncovered black matches only up to 3 kg; during laquering, imprinting, labelling only up to 20 kg, if the single article contains more than 50 g.
	b	30	2	
	c	30	0	Uncovered black matches during processing only up to 6 kg.
3	a	25	2	
	a	50	1	Articles with uncovered black matches only up to 30 kg.
	b	100	3	Quick matches in primary packagings and articles with uncovered black matches only up to 30 kg.
	c	100	0	Uncovered, non-pressed signal flares only up to 30 kg.
4	a	300	3	5 persons during laquering, imprinting, labelling, final assembling of finished, sealed components.
	b	500	as needed	
	c	500	0	
5	a	1500	as needed	
	b	6000	as needed	
	c	6000	0	

Table 6: Evaluation of safety characteristic data for the determination of the hazard number G

sensitivity	safety characteristic datum	maximum points	maximum value k	maximum hazard number G
thermal	ignition temperatur	10	100	300
	ignitability by sparks	10		
	ignitability by black powder fuse	10		
	ignitability by gas flame	10		
	ignitability by red-hot steel rod	10		
	combustion time in a red-hot steel bowl	10		
	limiting diameter in Koenen test	40		
mechanical	friction sensitivity	50	100	
	impact sensitivity	50		
to detonation shock	lead block expansion	50	100	
	behaviour in steel tubes	50		

Table 7: Hazard numbers assigned to hazard groups of the safety rules VBG 55 k

group	hazard number G
1	200 - 300
2	150 - 199
3	100 - 149
4	50 - 99
5	< 50

Table 8: Number of pyrotechnic compositions assigned to the five hazard groups of the VBG 55 k

substances	total number	number in hazard group				
		1	2	3	4	5
pyrotechnic compositions	51	16	12	16	7	0
black powders	13	0	4	9	0	0
binary mixtures	229	12	19	28	61	109
ternary mixtures	48	0	8	23	10	7
in total	341	28	43	76	78	116

Table 9: Descriptive terms of sensitivity related to safety characteristic data

Safety characteristic datum	Ranges of sensitivity data		
	very sensitive	sensitive	low sensitive
ignition temperature	≤ 280 °C	281 - 360 °C	> 360 °C
friction sensitivity	≤ 120 N	160 - 240 N	≥ 360 N
impact sensitivity	≤ 20 J	25 - 40 J	≥ 50 J

PYROTECHNICS IN THE ENTERTAINMENT INDUSTRY

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ABSTRACT

The subject of this article is how regulators and enforcement agencies, as well as producers, stage managers, and production managers can tell if the person about to perform or execute the pyrotechnic special effect is qualified to do so, and if he or she is a professional according to industry standards.

The term "Entertainment Industry" for the purposes of this article shall pertain to live stage productions such as the broadway show "Phantom of the Opera", or the Rolling Stones World Tour. It also encompasses motion picture and television productions. This is a relatively small and highly specialized industry and should not be considered part of the fireworks or blasting industry.

There are many times that the professional special effects technician will use pyrotechnics, explosives and propellants to enhance a particular scene. But how can you tell if the person about to use these materials is qualified to do so?

There are at least two (2) main criteria for determining this:

First: What type of work has this person done? It takes many years to qualify to become a professional special effects technician. This is done by working on an myriad of different productions under the jurisdiction of more experienced technicians to be qualified within the industry as a professional. There are no schools for this activity. Just by blowing up a car or shooting several flash pots does not, in our opinion qualify that person as a professional. Normally in the industry a bona fide production will hire an effects technician by word of mouth from one production company to another or by a recommendation from a recognized professional effects technician.

Second: What type of license does the person have? This is where I would like to elaborate somewhat.

Since the early seventies the State of California has had in effect Title 19 which outlines the licensing criteria as well as use restrictions in the industry.

As you are aware, California generates a tremendous amount of activity in the entertainment industry and as a result, there are a fair share of special effects technicians located there. Many of these technicians initially helped draft these current regulations. While there are other documents available which outline this industry, such as the National Fire Protection Associations #1126, there is no place that I am aware of in the world where a government agency provides particular licenses for special effects activities except in the State of California.

Title 19 was completely revamped in the years 1987 to 1991 to reflect the ever changing environment of this industry as well as that of the fireworks and rocket industry. Upon review you will notice that this document is not a "how to" nor does it attempt to place unnecessary restrictions on the technician or industry by telling the professional effects technician what material he/she may or may not use. You will also notice that Title 19 separates "fireworks" and "rockets" into different categories as well they should be.

Excerpts of Title 19

Article 3. Licenses

981. General

(a) No person shall engage in any type of fireworks activities without having submitted an application for and having a license from the State Fire Marshal in accordance with the provisions of this chapter. Licenses shall be processed in accordance with Title 19, California Code of Regulations, Section 3.33.

Exceptions:

(1) Licensed Pyrotechnic Operator's Basic Commercial, Restricted Commercial and Experimental Rockets may employ unlicensed assistants. Unlicensed assistants shall perform only when under the direct, immediate and constant supervision of the licensee when handling fireworks and pyrotechnic compositions.

(2) Licensed Special Effects and Theatrical pyrotechnicians may employ unlicensed assistants. Unlicensed assistants shall perform only when under direct, immediate and constant supervision of the licensee when handling fireworks and pyrotechnic compositions.

(3) A license shall not be required for the use or discharge of safe and sane fireworks.

981.9. License Scope

(a) Model Rockets. A Model Rocket License authorizes the manufacture, import, export or wholesale or any combination thereof.

(b) Pyrotechnic Operator. A Pyrotechnic Operator's license authorizes and places the responsibility for the handling, supervision and discharge of any fireworks item or pyrotechnic device and establishes that the operator is responsible for the training of his or her assistants in the safe handling, supervision, and discharge of these items and devices, in accordance with the following:

(1) Pyrotechnic Operator--Unrestricted may conduct and take charge of all fireworks activities in connection with every kind of public fireworks display, whether commercial entertainment, experimental and other types of rockets, or special effects in motion picture, theatrical and television production.

(2) Pyrotechnic Operator--Basic Commercial may conduct and is restricted to all fireworks activities in connection with a commercial fireworks public display, including the determination that all mortars, set pieces, rocket launchers and rockets are properly installed and that the proper safety precautions have been taken to insure the safety of persons and property.
Such operator shall have charge of all activities directly related to handling, preparing and firing all fireworks at the public display, including the fixing of lifting charges and quick match as needed for aerial shells.

(3) Pyrotechnic Operator--Restricted Commercial may conduct and is restricted exclusively to the use and discharge of firecrackers and the use of other exempt fireworks in religious ceremonies.

(4) Pyrotechnic Operator--Rockets First Class may conduct and is restricted to all activities in connection with research experiments, production, transportation, fuel loading and launching of all types of solid fuel experimental rockets only. Such operator shall also be responsible for the actions and conduct of all assistants. Operators licensed under this subsection (b) are also required to obtain a local permit from the authority having jurisdiction prior to all launches.

(5) Pyrotechnic Operator--Special Effects First Class may conduct and is restricted to the use, preparation for transportation and the preparation and use of all types of fireworks and special effects pyrotechnics, for the sole purpose of producing a visible or audible effect where and when such use is a necessary part of motion picture, television, theatrical or operatic production, as permitted by the fire authority having jurisdiction.

(6) Pyrotechnic Operator--Special Effects Second Class may conduct and is restricted to the use of special effects, the loading of blank cartridges, colored fire, flash paper, smoke composition, the preparation and use of binary a and b flash composition, and such other fireworks of whatever kind and class as may be permitted by the authority having jurisdiction, under special permit in connection with television and motion picture production.

(7) Pyrotechnic Operator--Special Effects Third Class authorizes the loading of blank cartridge shells, and use of special effects when under the direct supervision and control of a Pyrotechnic Operator--Special Effects First or Second Class.

(8) Pyrotechnic Operator--Theatrical authorizes the use of special effects, blank cartridges, colored fire, flash paper, flash, smoke composition, and the preparation and use of binary a and b flash composition in stage or theatrical productions only.

(9) Pyrotechnic Operator-Theatrical Trainee authorizes the conducting of procedures permitted a Pyrotechnic Operator--theatrical when under the direct supervision and control of a licensed Pyrotechnic Operator--Theatrical.

(10) Pyrotechnic Operator--Performer is restricted to persons who perform before an audience, directly or indirectly, and may include magicians, comedians, still photographers, and others whose primary interest is in other than pyrotechnics. Such license is restricted to the use of special effects, blank cartridges, colored fire, flash paper, sparklers, smoke composition in connection with the production of theatricals and operas before live audiences in theaters, opera houses, television studios, night clubs, and similar occupancies, or by the use of a still photographer.

(c) Separate license not required. A separate license shall not be required of licensed manufacturers, wholesalers, or importer-exporter to manufacture, wholesale, import or export agricultural and wildlife fireworks or model rocket engines.

(d) Explosive material not included in scope of license. The license scope as defined in this section is restricted to the use of materials defined as "fireworks" (as defined in Health and Safety Code Section 12511) and in no way confers authority for the use or discharge of explosive materials defined in Health and Safety Code Sections 12000, et.Seq.

Article 5. Qualification--Examination and Investigation

984. General

(a) Test and examination. Every applicant for a pyrotechnic operator's license shall take and pass a written examination administered by the state fire marshal in accordance with the provisions of this chapter. The applicant shall submit evidence attesting to the qualifications and experience required by this article for the type of license for which application has been submitted.

(1) Pyrotechnic Operator--Unrestricted shall require a minimum amount of experience as indicated for each of the following types of licenses. Such experience shall be in the actual discharge of fireworks and pyrotechnic devices for the types indicated.

(A) Pyrotechnic Operator--Basic Commercial	2 Years
(B) Pyrotechnic Operator--Rockets First Class	2 Years
(C) Pyrotechnic Operator--Special Effects First Class	2 Years

Under the provisions of this section, not less than 6 years total experience is required.

(2) Pyrotechnic Operator--Basic Commercial shall require a minimum of 2 years of active work as an unlicensed assistant to either a licensed Pyrotechnic Operator--Unrestricted, or Basic Commercial. This time requirement may be reduced by 1 year through the successful completion of a State Fire Marshal approved training course or through exceptional work experience as evidenced by log entries or work records. Notwithstanding the 2 year requirement, the applicant shall have participated in the firing of not less than 8 different public displays.

(3) Pyrotechnic Operator--Special Effects First Class shall require a minimum of 2 years of active work as a Pyrotechnic Operator--Special Effects Second Class. This time requirement may be reduced by 1 year through the successful completion of a State Fire Marshal approved training course or through exceptional work experience as evidenced by log entries or work records.

(4) Pyrotechnic Operator--Special Effects Second Class shall require a minimum of 2 years of active work as a Pyrotechnic Operator--Special Effects Third Class. This time requirement may be reduced by 1 year through the successful completion on a State Fire Marshal approved training course or through exceptional work experience as evidenced by log entries or work records.

(5) Pyrotechnic Operator--Special Effects Third Class. No experience required.

(6) Pyrotechnic Operator--Theatrical shall require a minimum of 2 years of active work as a Pyrotechnic Operator--Theatrical trainee. This time requirement may be reduced by 1 year through the successful completion of a State Fire Marshal approved training course or through exceptional work experience as evidenced by log entries or work records.

(7) Pyrotechnic Operator--Theatrical Trainee. No experience required.

(8) Pyrotechnic Operator--Performer. No experience required.

(b) Qualifications. Adequate qualification for the issuance of the requested license shall be determined by the State Fire Marshal. It shall be incumbent upon the applicant to present to the state fire marshal evidence of such qualifications which may include a physical demonstration of knowledge and ability.

(c) Experience. The required experience for issuance of a Pyrotechnic Operator's license shall be in accordance with this section. In addition, applications shall be accompanied by the names and complete addresses of not less than five persons as reference who are not a relative, and who can attest to the applicant's experience, integrity and training. The references shall be licensed Pyrotechnic Operators of a class equal to or greater than the class applied for and shall have been licensed for at least one year.

984.1. Examinations

984.1. Examinations. The written examination required for Pyrotechnic Operators shall consist of at least three parts, one pertaining to laws relating to fireworks, one pertaining to regulations relating to fireworks and one relating to the practices and procedures of the license scope.

984.2. Examination process.

(a) To satisfactorily pass the written examination, the applicant must obtain a minimum grade of seventy percent (70%) in each part.

(b) Every person taking an examination for Pyrotechnic Operator shall have the right to contest the validity of individual questions of such examination.

(c) Every objection as to the validity of individual questions of an examination shall be made in writing within 5 days after taking said examination. Objections shall state the reasons for the objection.

(d) The decision as to the action to be taken on the submitted objection(s) shall be by the State Fire Marshal and such decision shall be final.

(e) The decision made by the State Fire Marshal and the action taken shall be reflected in all future examinations but shall not affect the grades established in past examinations.

(f) Any applicant failing the examination may reapply and take another examination not less than 15 days from the date of the previous examination.

(g) Applicants applying to take repeat examinations shall file a new application. An additional fee is not required in those instances where the applicant has taken a test and failed it.

(h) The State Fire Marshal may require a reexamination of any licensee. This examination may be of any type permitted by these regulations. A fee shall not be required for a reexamination.

(i) Any applicant found using any extrinsic aids during the examination shall automatically fail the examination, and shall forfeit admission to future examinations for a period of one year.

984.3. Application period

984.3. Application period. An original Pyrotechnic Operator's license shall not be issued for the month of June of any fiscal year unless the application has been received in the office of the State Fire Marshal on or before the preceding May 15.

984.4. Investigation

984.4. Investigation and letters of reference. Applicants for a Pyrotechnic Operator's license are subject to an investigation by the State Fire Marshal. The investigation is intended to determine, but will not be limited to, compliance with state laws and regulations, and competency of applicant to perform in a safe manner. To assist in this investigation five letters of reference verifying that the applicant's experience, integrity and training substantially meet the class of license applied for in conformance with section 984(c) shall be submitted with this application. A review of the applicant's log or journal detailing the kind of materials used, the quantity, how fired, date, time and location, and name and license number of the supervising Pyrotechnician.

These Regulations would make a good guideline for other people or government agencies to refer to or adopt. For more information pertaining to Title 19 feel free to contact the State Fire Marshals Office in Sacramento, CA.

REFERENCES

[1] **CALIFORNIA STATE FIRE MARSHALS OFFICE,** "California Administrative Code, Title 19, California Explosives Law & Regulations"

[2] **NATIONAL FIRE PROTECTION ASSOCIATION 1126**

EUROPEAN STANDARDISATION OF FIREWORKS CEN TC/212:

A REVIEW OF THE CURRENT POSITION

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ABSTRACT

Work began on a British Standard for fireworks in 1985 and BS 7114 Fireworks was published in 1988. European Standards for fireworks was started in 1989, using the BS as the base document. The main Technical Committee, CEN/TC/212, is supported by three Working Groups, WG1 classificiation and terminology, WG2 labelling and WG3 requirements and test methods.

CEN/TC/212 has followed the BS system of dividing fireworks into four categories. Requirements for individual types of firework will be set. Compliance with the requirements will be monitored by type and batch testing. Many issues have still to be resolved and the technical work programme of CEN/TC/212 has a provisional completion date of March 1997.

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INTRODUCTION

Work began on a British Standard (BS) for fireworks in 1985, the technical committee and working groups comprised representatives from the United Kingdom fireworks industry, government departments and associations with consumer interests.

BS 7114:1988 was promulgated in 1988 and adopted by the Secretary of State for Trade and Industry as an approved standard for the purposes of Section 10(3) of the Consumer Protection Act in March 1989. The standard applies to fireworks for sale to the general public, for indoor and outdoor use and is in three parts.

Part 1 Classification of fireworks; Part 2 Specification for fireworks; Part 3 Methods of test for fireworks. The requirements of the BS included categorisation, quality control, labelling and performance testing. Rapley and Thomson presented a paper giving the background to this national standard in 1989 (reference 1).

Work started on the European Standards in 1989 and draft requirements for many types of firework were prepared using BS 7114:1988 as a basis. The first meeting of CEN TC/212 established the scope of the standard and the system of work. The scope was defined as "Ready for use pyrotechnic articles for entertainment purposes, particularly from the point of view of their safe use" and the BS was taken as the base document. There is a main technical committee, with three working groups reporting to it. Working Group 1 deals with classification and terminology, Working Group 2 with labelling and Working Group 3 with requirements and test methods. Pfeil and Andre summarised the early work of CEN TC/212 in a paper published in 1991 (Reference 2).

The main technical committee of CEN TC/212 meets once a year in order to oversee the work of the Working Groups, monitor progress and to agree objectives and resolutions. The Working Groups meet more frequently, generally three times a year. Countries sending experts to the main technical committee and the working groups are Finland, France, Germany, Italy, Netherlands, Spain, Sweden and United Kingdom.

I am the Convenor of Working Group 3 "Requirements and Testing" which carries the main workload for CEN TC/212. The present paper outlines the current position and future targets of WG3.

CATEGORIES

CEN TC/212 has agreed that there will be four categories of firework, this is in line with base document BS 7114:1988. They can be described briefly as follows:

Category 1 will contain fireworks which present a low hazard and will include all the indoor fireworks.

Category 2 will contain fireworks which present a low hazard and which are intended for outdoor use in confined areas.

Category 3 will contain fireworks which present a medium hazard and which are intended for outdoor use in large, open areas.

Category 4 will contain fireworks which present a high hazard and which are intended for professional use only.

TYPE AND BATCH TESTING

A batch testing system involves performance testing of samples from production batches of fireworks. The British Standard uses sampling procedures from BS 6001: Part 1 (ISO 2859-1:1989). In this system, failure to meet a requirement results in a nonconformity, which can be classed as critical, major or minor. An Acceptable Quality Level (AQL) is then applied to the number and type of nonconforming units to decide on whether a batch is acceptable. Some countries already had a type testing system in place. Type testing is not a continuing system, a set number (e.g. 10) of fireworks are tested and every firework in the sample must meet all the requirements. There is no provision for further testing.

The CEN standard will contain both type and batch testing. Generally type testing will apply to all requirements and batch testing will monitor visual and performance tests only. Table 1 uses the draft specification for bangers to illustrate the requirements against type and batch testing.

The current proposal is to take a sample of 30 fireworks for the type test: 10 of these are to be tested as received, 10 are to undergo thermal conditioning for 4 weeks at 50 +/- 2.5 °C before testing, and 10 are to undergo mechanical conditioning at an acceleration of 490ms^{-2} with a frequency of 1Hz for 2 hours before testing. All 30 fireworks must meet all the type test requirements. Batch testing will use ISO 2859 (reference 3). Special Inspection level S-4 will determine the sample size to be taken, examples of the number of items this will involve are given in Table 2. The AQL's will determine if a batch is accepted or rejected and the proposed values are 0.65 for critical nonconforming units, 2.5 for major nonconforming units and 10 for minor nonconforming units. Table 3 shows the double sample plans for normal, reduced and tightened inspection. The standard will use sample plans and apply switching procedures for normal, tightened and reduced inspection, see Figure 1.

TESTING DISTANCES

In the British Standard, distances were given at which the fireworks should not cause injury to people when they were used according to the instructions. For Categories 1, 2 and 3 these distances were 1m, 5m and 25m respectively. The testing distance for category 2 was 3m and 20m for category 3. Because category 1 contained so many different types of firework, the testing distance varies.

For the CEN standard, a range of testing distances from 2m to 8m for category 2, and 10m to 25m for category 3 were the first proposals by the WG3 members. The general feeling was that testing distances should take in to account correct use, possible misuse and possible malfunction. WG3 has discussed this important issue in some detail (using category 2 bangers as an example). A compromise position has been reached involving two testing distances for category 2, which depend on the different levels of debris.

The provisionally agreed testing distances for the different categories of firework in the CEN standard are:

Category 1	1m (this will vary for many types within this category)
Category 2	6m for dangerous debris weighing more than 1g, and 8m for no debris
Category 3	15m for no debris

As draft specifications for more fireworks are prepared these distances will receive further consideration. Ideally, testing distances should apply to all, or at least the majority, of firework types within a category.

INITIAL FUSE BURNING TIMES

The principle behind the fuse burning times in the BS was that for category 2, 3-13s represented the minimum time that would allow the operator to retreat to the spectator distance of 5m and the maximum time that would prevent a person returning too soon to a functioning firework. For Category 3 the lower limit of 5s was to allow the operator time to retreat a further distance away from the larger fireworks involved. The upper limit was set at 15s although the operator would not always be expected to retreat to the spectator distance.

This important issue has had much discussion in WG 3. All experts agree that there should be a minimum and maximum initial fuse burning time. At the time of writing (January 1992) details have not been fully resolved but the times under consideration are:

Cat 1	Most items do not have an initial fuse burning time
Cat 2	Minimum 3 and maximum 8/13s
Cat 3	Minimum 3/5 and maximum 8/15s

The United Kingdom experts feel very strongly that the minimum time of 5s for category 3 items should be maintained. They also feel that with items such as Category 3 shells, the operator must be given sufficient time to move to a safe distance from the functioning firework.

CONSTRUCTION AND COMPOSITIONS

CEN TC/212 is not intended to provide instruction on how to make fireworks. There will be certain fireworks where the composition is specified e.g. category 2 bangers contain only black powder, and flash bangers contain a pyrotechnic composition containing metal powder. The size and explosive content of fireworks may be included in certain specifications. This will usually be for classification purposes i.e. to demarcate between category 2 and category 3 items of the same type.

The demarcation will mainly concern the distinction between categories 2 and 3. There are many types of firework that are common to both categories. One of the main tasks of WG3 is to consider all the contributing factors such as type of firework, principal effect, correct functioning, size, explosive content, noise level and foreseeable misuse. The requirements will then be set at the level appropriate to the hazard.

NOISE LEVEL

When the BS was being formulated there was no agreed position in Europe regarding the level of impulse noise that could cause damage to hearing. Consequently a requirement for a maximum noise level was not included in the standard. For certain types of firework e.g. banger, the maximum explosive content was set at a level that would limit the noise produced. An EEC directive on the protection of workers from the risks related to exposure to noise at work was published in May 1986 (reference 4). This directive set a cumulative limit and an instantaneous exposure limit. Working Group 3 has decided that the CEN standard will include a maximum noise level for fireworks. A paper presented by Smoorenburg (reference 5) to WG3, gives levels of exposure to impulse noise that can cause damage to hearing. Data are required from more sources so that an informed decision on the maximum impulse noise level can be made. The Working Group will then have to consider a test method which will have to take into account the likely distances of spectators relative to impulse sound sources.

FUTURE WORK

Working Group 3 must undertake work in many areas before certain specific issues are resolved.

Aerial fireworks such as rockets and shells have yet to be fully debated and requirements covering angle of flight, minimum height of burst and falling debris have to be discussed.

A decision will have to be made on the ignition source to be specified for testing purposes. The United Kingdom experience of timing initial fuse burning times when batch testing fireworks has indicated that this could be a problem area. Different ignition sources give different heat outputs, flame size and burning temperatures. This difference introduces an additional variable that could affect the result of the test. Ideally the ignition source should consistently light all types of fuse and yet not affect the initial fuse burning times. Custom and practice for lighting fireworks (although not necessarily for testing purposes) in different countries has led to almost as many preferred ignition sources as there are countries.

The question of exposure to noise levels for spectators and operators has been mentioned in the previous section and further work and consideration will need to be given to this subject before a decision is taken.

I will strongly recommend that each draft specification is tested by all countries before it is finalised. This will ensure that each specification is appropriate and practical.

TARGET DATES

There are 45 different types of firework on the CEN TC/212 work programme and Working Group 3 will have to consider requirements and test methods for all of them. The types have been allocated three levels of priority:

High priority (11 types) - included in this group are items such as bangers and fountains, the specifications of which include requirements that are common to many types and therefore agreement on basic issues, once resolved, will speed up the overall drafting process. Shells and rockets are included because they represent aerial fireworks that present a high hazard.

Medium priority (16 types) - included in this group are items such as vertical wheels, the specifications of which include many aspects covered by high priority items but are widely used and have some unique requirements.

Low priority (18 types) - includes such items as aquatic shells, that do not have a wide usage or present a low hazard.

When the working groups have agreed on the contents a draft standard is forwarded to the TC for approval. The TC Secretariat then prepares a final text which is forwarded to the CEN Central Secretariat for distribution to the CEN members for public comment.

Having received and considered public comments from the enquiry stage, an agreed text will then be forwarded to the

Technical Committee for approval . A final text is then prepared by the Technical Committee Secretariat and forwarded to the CEN Central Secretariat for a formal vote by members.

The timetable of CEN TC/212 for high, medium and low priority work is as follows:

Enquiry	Formal vote	
High priority	1993 December	1995 March
Medium priority	1994 December	1996 March
Low priority	1995 December	1997 March

CONCLUSIONS

Working Groups 1 and 2 will continue meeting to finalise their position on categorisation and labelling. The areas that WG2 still have to make decisions on are: correct phrases, print size, positioning of label and the number of languages on each label.

Working Group 3 has four years in which to present all the draft specifications to the main technical committee of CEN/TC/212. Although the pattern of meetings may vary in the latter stages, it is likely that about twelve more meetings will be held. It is hoped that fruitful discussion, practical work, negotiation and compromise will produce CEN standards for fireworks that meet the objectives of all participating countries.

The preparation of standards is a time consuming business and the larger the number of organisations represented, the longer the time required. A national standard like the British Standard took three years to complete. The projected dates indicate that completion of the European Standards would have extended over nine years. Bearing these time scales in mind, a better way forward might be to develop regional and national standards that are aligned as closely as possible.

REFERENCES

1. Rapley R J, Thomson B J, 14th International Pyrotechnics Seminar, Jersey, 1989 (pages 393-402)

2. Pfeil N, Andre H, 16th International Pyrotechnics Seminary, Jonkoping, 1991 (pages 289-303)

3. ISO 28598 "Sampling procedures for inspection by attributes, Part 1 Sampling plans indexed by acceptable quality level (AQL) for lot-by-lot inspection"

4. The Council of European Communities "Council Directive of 12 May 1986 on the protection of workers from the risks related to exposure to noise at work" 86/188/EEC (May 1986)

5. Smoorenburg G F, "Risk of noise-induced hearing loss with exposure to Chinese firecrackers" Committee paper CEN/TC/212/WG3/N27

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TABLE 1: PROPOSED REQUIREMENTS FOR BANGERS

REQUIREMENT	TYPE TESTED	BATCH TESTED
INITIAL FUSE	YES	YES
Initial fuse shall be secure	YES	YES
Initial ignition of the fuse shall be visible	YES	YES
PROTECTION OF INITIAL FUSE	YES	YES
MATERIAL OF FIREWORK CASE	YES	YES
INTEGRITY OF FIREWORK CASE	YES	YES
PYROTECHNIC COMPOSITION	YES	NO
NET EXPLOSIVE CONTENT	YES	NO
PERFORMANCE		
Initial fuse burning time	YES	YES
Principal effect	YES	YES
Explosion	YES	YES
Burning matter	YES	YES
Projected debris	YES	YES
THERMAL STABILITY	YES	NO
MECHANICAL STABILITY	YES	NO
MAXIMUM NOISE LEVEL	YES	YES
INTEGRITY OF PRIMARY PACK	YES	YES
LABELLING	YES	YES

TABLE 2: SIZE OF SAMPLE, USING SPECIAL INSPECTION LEVEL 4

LOT OR BATCH SIZE		FIRST SAMPLE	SECOND SAMPLE
501	1 200	13	13
1 201	3 200	20	20
3 201	10 000	20	20
10 001	35 000	32	32
35 001	to 150 000	50	50
150 001	to 500 000	50	50
500 001 and over		80	80

TABLE 3: ACCEPT/REJECT CRITERIA AT AN AQL OF 2.5
USING DOUBLE SAMPLING PLANS AND SWITCHING PROCEDURES

BATCH SIZE	NORMAL INSPECTION Major Nonconformity			REDUCED INSPECTION Major Nonconformity			TIGHTENED INSPECTION Major Nonconformity		
	Sample Size	Accept	Reject	Sample Size	Accept	Reject	Sample Size	Accept	Reject
501 - 1 200	13	0	2	5	0	2	20	0	2
	26	1	2	10	0	2	40	1	2
1 201 - 3 200	20	0	3	8	0	3	20	0	2
	40	3	4	16	0	4	40	1	2
3 201 - 10 000	20	0	3	8	0	3	20	0	2
	40	3	4	16	0	4	40	1	2
10 001 - 35 000	32	1	4	13	0	4	32	0	3
	64	4	5	26	1	5	64	3	4
35 001 - 150 000	50	2	5	20	0	4	50	1	4
	100	6	7	40	3	6	100	4	5
150 001 - 500 000	50	2	5	20	0	4	50	1	4
	100	6	7	40	3	6	100	4	5
500 001 - over	80	3	7	32	1	5	80	2	5
	160	8	9	64	4	7	160	6	7

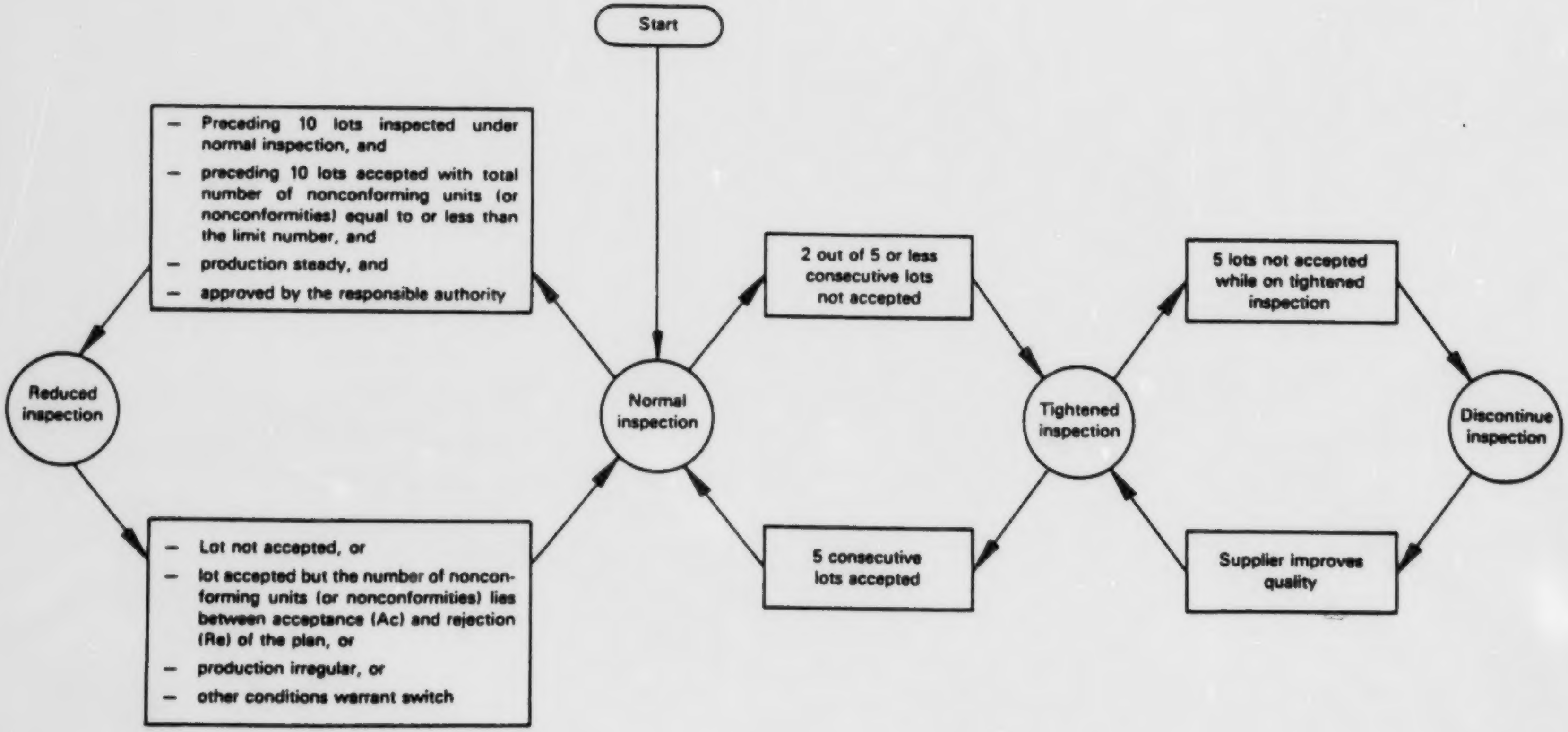
Start
Reduced inspection
– Preceding 10 lots inspected under normal inspection, and
– preceding 10 lots accepted with total number of nonconforming units (or nonconformities) equal to or less than the limit number, and
– production steady, and
– approved by the responsible authority
– Lot not accepted, or
– lot accepted but the number of nonconforming units (or nonconformities) lies between acceptance (Ac) and rejection (Re) of the plan, or
– production irregular, or
– other conditions warrant switch
Normal inspection
2 out of 5 or less consecutive lots not accepted
5 consecutive lots accepted
Tightened inspection
5 lots not accepted while on tightened inspection
Supplier improves quality
Discontinue inspection

Figure 1 — Outline of the switching rules

PROBLEMS WITH MUSIC FIREWORKS WITHOUT HELP OF MUSICAL INSTRUMENTS

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The so called "Music Fireworks" are generally the firework displays in combination with some music from musical instruments. However, fireworks produce several types of loud noise or whistling sound. I have heard from a musician of avant-garde "Any sound or noise could be used as music." Therefore, I tried in the past to compose the firework sounds into a music without any help of other musical instruments. I fairly succeeded at PL Festival in Osaka 1965, but next year failed and thought there were many problems to be solved.

The sound sources of several types are suggested for the music fireworks: the noise of shot, explosive noise of shell break, bangs and whistles etc. They could be used like the sounds of percussion instruments, e.g., bass or side-drums or flute etc.

The most important and fundamental proplem is to make a rhythm with firework sounds. When we could make it, we could produce a strange new music. To compose above types of sound, the time accuracy of the firework effects is the most important. Of course, it must be done safely and not expensively. For this purpose electronic devises may be helpful in some extent, but not almighty. Firstly we must design the fireworks so that the accuracy would be obtained only by pyrotechnics by itself.

Following above considerations, the proper time intervals of beats, permissible deviations of ignition delays, designs of firework sound drvices, methods of composition using firework sounds and the problem of speed difference between sound and light neams were discussed experimentally or from my experiences.

1. INTRODUCTION

Recent years so called "music firework dispays" are widely in fashion. They aim a cinematic effect of fireworks in combination with some music from musical instruments. The idea is too common to develope fireworks themselves. Moreover, firework noises are always loud and ordinary music instruments produce only low sounds. The latter must be powerfully amplified when we expect the musical effect overcoming the former. This is an expensive effort.

Fireworks produce various types of sound. My idea is to use these sounds as music elements to compose a firework music following a rhythm without any help of music instruments. Hereby, an acculate time control of the firework sounds becomes an important problem. In this case, the sound sources are always moving in the air except few noises. Therefore, another important problem, the space control of sounds by ballistics, should also be in consideration.

2. THE TIME CONTROL OF THE FIREWORK SOUNDS

2.1. Rhythm

Any firework sound could be used as a music element when it is timely arranged in a rhythm. From my experience, the proper number of beats per minute for firework music should be 40-72, i.e. Largo. When the tempo is slower than Largo, we do not feel music effect. On the contrary, when the tempo is faster than Largo, the time control of sound effects is pyrotechnically difficult. When using various electronic ignition devices for the sound elements may be effective to make the control more easy and the tempo more fast than the Largo, but we should possibly avoid such an expensive method. The accuracy of the time intervals between the beats is the most important in the time control. When the deviations are too large, we cannot feel a music with the sounds. The allowable values of the deviation are not yet experimentally confirmed, but it should be within 15% of one interval. However, too large deviations sometimes give us a feeling like a syncopation.

The rhythm could be composed of several firework sounds, e.g., noise of shot(Dong), noise of report(Bang), noise of small shell break(Pang), noise of large shell break(Dang), noise of many small cracks(Jang), noise of hummer (Brun) and sound of whistle(Hyuu) etc. The first six resemble the sounds of percussion instruments and only the last one is a musical sound. The onomatopoeias used above come mainly from my feelings.For simplicity, I hereafter use these words. For example, the rhythm of a single shot may be composed as follows:

Dong -- Bang -- Bang -- Pang -- Hyuu -- Brun

where the time intervals are one second and the practical operations of the elements are showen in Figure 1. In this case one music unit consists of six elements. In addition, the ranks of sound intensity are introduced to produce a vivid effect. The quantity of pyrotechnic compositions or the size of shells should be selected for the purpose. From these considerations, a firwork musical note could be planned (Figure 2).

2.2. Element of the sound

(1) The noise of shot (Dong)

In the lifting place it is very loud, but from a distance of 100 meters it is weak and soft. Therefore, it is suitable to start a music or a music section. because they should be started from soft sounds. The fire from the mortar gives a good previous notice of the beginning of the music before the sound to the audience who are at a distance from the firing position.

(2) The noise of report (Bang)

It is a sharp and loud noise from an aluminum and perchlorate composition. The intensity of the noise is easily adjustable changing the weight of the mixture, i.e., from 5 grams to 30 grams or more. This noise sounds not so unpleasant as a noise of detonation of a high explosives, but even comfortable at a proper distance. The detonation velocity of this type of composition is about 1200 meters per second and that of high explosives is about 5000-7000 meters per second (1). The report might soften perhaps because of the low detonation velocity. I often call this type of noise a "round noise" which means a noise without thorn.

(3) The noise of small shell break (Pang)

This is a sound of a small shell break in the case of Poka which contains only a small quantity of bursting sharge. When it comes from the sky, we often fail to catch it. It is often necessary to reinforce it by increasing the quantity of the bursting charge.

(4) The noise of large shell break (Dang)

This is the largest noise of all others and strongly affects ones feelings. Someone hates this type of noise. Therefore, the unpleasant effect of the noise should be minimized by decreasing the bursting charge as far as possible. However, there is a limit of the quantity of the charge, because it must produce energy to create a chrysanthemum.

(5) The noise of hummer (Brun)

This is a humming sound which is produced by a small pyrotechnic device (Figure 5,6). It gives the audience a very curious feeling. When a large number of pieces are used, they sound like a large crowd of bees.

(6) The sound of whistle (Hyuu)

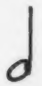
This is an only musical sound which can be produced by a pyrotechnic device (Figure 3). The sound resembles that of a flute. The scale of sound is adjustable in some extent by changing the length of pipe like Do, Re, Mi, .. (Figure 4). The sound comes from a vibrational burning of a pyrotechnic composition. Generally, the scale of the sound changes with time when no special device is added. It may be an important problem in future.

(7) The noise of many small cracks (Jang)

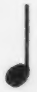
Generally, this sound comes from instantaneous explosions of many stars.A special noise composition is used in each star as a core. After a burning time it cracks. When a shell which contains many such stars bursts in the sky, a compound sound like "Jang" comes to the audience. (Figure 9)

2.3. The firework note

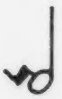
For the time arrangement of sounds, I propose here to use following notes as it is in a music.



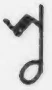
Pang,a break sound of Poka shell which contains a smaller bursting charge. The round circle denotes a shell and the tail shows some other effects added before the sound Pang.



Dang, a break sound of Warimono shell which contains a larger bursting charge. Others are the same as above.

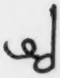


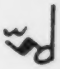
Pang--Bang, which denote a Pang and after one beat a Bang. In this case the sound element of the Bang is contained in the Poka shell.

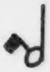


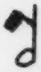
Bang--Pang, which denot a Bang and after one beat a Pang. In this case the sound element of the Bang is fixed to the tail.

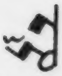
In the same way, other type of sound elements are denoted adding their symbols to the main shell symbol:


Pang--Brun.

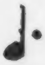

Pang--Jang.

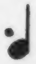

Pang--Hyuu.

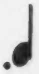

Hyuu--Pang.

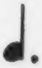

Hyuu--Pang--Jang.

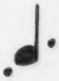
With the firework display, other important problem arises: how to match the music with the light effect. It is very complicated, but I present here a method to use notes which denote color changing in the case of chrysanthemum (2):

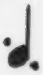

red,


yellow,


green,

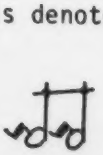

blue,

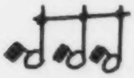

green to red,


blue to yellow.

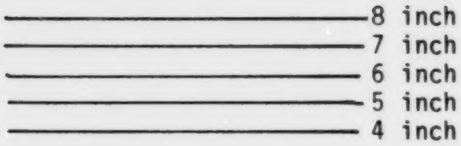
Each color should be changed with one beat.

A combination of two shells or three shells which are shot at the same time is denoted as follows:

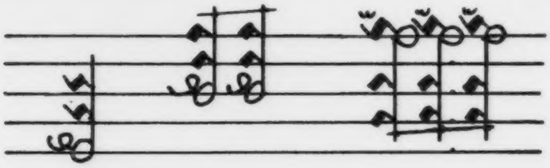

a two shell combination with Bang + Bang.


a three shell combination with Hyuu + Hyuu + Hyuu.

To denote the diameters of shells, five lines are used:



Then a progress of some dispay is denoted as follows:



where it shows sounds: Dong--Bang--Bang--Pan--Brun--Dong--Hyuu--Hyuu--Pang--
Dong--Hyuu--Hyuu--Pang--

Brun
Brun-- Dong--Hyuu--Hyuu--Pang--Jang
Dong--Hyuu--Hyuu--Pang--Jang . The sounds become louder and louder with
Dong--Hyuu--Hyuu--Pang--Jang

increasing the shell sizes and bustling with increasing the number of shells in a combination.The sounds from one shell in this example consist of five beats.

2.3. Construction of the sound elements

The sound elements,i.e.,the noise producing devicesmust be resistant to the shock and firmly fixed to the shell when they are added to the shell from outside of it. They should not react against each other in the trajectory of the shell. When they are contained in the shell, they must be resistant to the pressure when bursting.

Figure 5 shows a report(Bang). Such a round form is very resistant to the shock and pressure. The hemp tail is used to tie to the tail of the shell (Figure 2). Figure 6 shows an element which contains microstars and bursting charge. The effect resembles that of the report, but not only the report, but also a small flower.

Figure 7 shows a hummer(Brun). These many pieces are contained in a shell and they are ignited at the same time when bursting. They move spirally in air and make a curious sound.

Figure 8 shows a whistle(Hyuu). The tail is used to tie to the tail of the shell as it is with Fighue 5, a report. The hollow end is covered with a piece of strong kraft inserting a piece of black match. The end should be reinforced to avoid its detonation by the burst when it is enclosed in a shell.

Figure 9 shows microstars of cracks(Jang). The core consists of red explosive (3). The cores are made as follows. The red explosive mixture (potassium chlorate/realgar: 7/3 in weight ratio) is carefully prepared shieving it very gently. It is made wet adding a quantity of water. The mixture is spread in a long line on a sheet of Japanese paper and wound with the paper gently by hand like a long fuse. It is covered with a wet towel until the paper absorbs moisture and becomes completely wet. Then the long fuse is cut into short pieces of about 6-8 mm long while it is still wet. They are dried in room pemperature. They are covered with other delay mixtures,for example a colored flame mixture which contains no sulphur and then a black type mixture for ignition, as it is in the case of manufacturing ordinary stars. The delay time shoud be the same as the time interval of beats.

The manufacturing of the microstars of cracks(Jan) is dangerous. Therefore, many pieces of small Bangs called "Thousands of Bang" are sometimes used in place of Jang when the manufacturer is unfamiliar with the cracks.

The delay time or the time of effect must be the same with the time interval of musical beats. On manufacturing the sound elements or the shell the workers must pay the most scrupulous attention to this point. Pieces of Bickford fuse are often conveniently used for the delay (a time fuse). The time deviations occur in this case between the following steps:

A	B	C	D
Ignition to the fuse end by black match or a squib	Burning of the fuse	Fire transfer to mixture from fuse burst	Action of the sound element

For example, when a time fuse of 2 seconds is used, the maximum deviation between A and B may be 0.01 seconds, B and C also 0.01seconds and C and D 0.2 to 0.7 seconds according to the construction of the sound element, i.e., the largest deviations occur between C and D. To minimize the deviation an intensive ignition mixture should be used between C and D. For example, a boron/potassium nitrate in weight ratio of 3/7 is very effective (4). It would be not so expensive because only a small quantity will do for the ignition.

When holes are punched near the ends of the piece of fuse, the part of the fuse should not be deformed as it is shown in Figure 10. Otherwise, the time deviation increases because of the break of the core composition.

3. THE SPACE CONTROL OF THE FIREWORK SOUNDS

3.1. The movement of the sound elements

In general, when the sound elements produce sounds at the same time intervals and at the same position, they can create a rhythm. However, when the elements move with the movement of the shell, to which they are fixed, the rhythm is disturbed, because the time intervals of the sounds do not reach with those to the audience. Therefore, when the correct time intervals are desired, the delay time of each element should be altered according to the time intervals of the beats so that the audience feel the correct rhythm. It seems very complicated because the delay times of the fuse pieses, i.e., the lengths of the fuse pieces, must be different each other according to the distance between the sound position and the audience. Moreover, the trajectory of the shells are different each other according to the shell size, and the length of the delay fuse must be also changed according to the shell size.

A simplifying method may be:

(1) making the maximum ascending heights of shells same, for example, 200 meters, regardless of the shell sizes by increasing or decreasing the quantity of the lifting charge,

(2) selecting only 5 inch and 6 inch shells for the display, because it is difficult to adjust the lifting charge to the height of 200 meters with other shell sizes.

A calculation shows, when the maximum height of the shell is 200 meters and the audience are 200 meters distant from the lifting place, the delay times of the sound elements from the start (shot) for one second interval:

first beat:	0.00 second,
second beat:	0.98 seconds,
third beat:	1.96 seconds,
fourth beat:	2.88 seconds,
fifth beat:	3.82 seconds,
sixth beat:	4.78 seconds.

The time fuse should be adjusted to match the time values. As it is seen, the deviations of the time intervals are not so large from the standard, 0, 1, 2, 3, 4, 5 seconds. Therefore, we could sometimes ignore the deviations when the conditions of display are not so fifferent from the above.

3.2. Deviation of the trajectory

When a shell is very carefully shot from a mortar, which is set vertically, the shell does ont rise vertically to make a deviation. A good rhythm could be obtained by minimize such a type of space deviation with trajectory.

The deviation of the trajectory of the shell from the vertical may be caused by complex conditions, the weight of shell, quantity and intensity of lifting charge, clearlance between the inside of mortar wall, and air conditions, especially wind velocity etc. In the past, I experimentally found a large deviation generally comes from the spin of the shell, even when other conditions are kept possibly constant. Figure 11 shows the result of the experiment (5). The horizontal lines show distances from the mortar to the positions where dummy shells fell onto the ground. The shells were 4.76 inches (4 sun) and 5.95 inches (5 sun) in diameter. Each size shells had the same weight, but a half of them were respectively fixed with a length of tail as it is in Figure 2, but no sound element. The purpose of the tail is to stop the spin of the shell in the air. Each of the shells was lifted in a same firing condition. The shells which fell on to the ground are denoted with a round symbol with or without a tail. The results clearly show that the shells with a tail make a smaller deviation than the shells without tail, i.e., the spin of a shell enlarge the deviation which can be minimized by stopping it by the tail effect.

3.3. The distance of the audience from the lifting place

As described above, when 5 or 6 inch shells are used for a firework display and the audience are distant more than 200 meters from the firing position, a firework music will be effective, however, only the auditory effect will be successfully obtained. However, in the case of firework display the visual effect should be also combined with it. It is a very difficult problem because of the large difference between the velocities of sound and light beams. The sound velocity in air is about 330 meters per second and that of the light beams about 300,000 kilometers per second. To match the both effects the audience must keep a distance, 165, 330, 495 or 660 meters (sound velocity is multiplied by 1/2, 1, 3/2, or 2) etc. from the firing position when the time intervals of beats are one second.

The place, where the mortars are set, should be possibly narrow to minimize the time deviations of the beats.

4. SAFETY PRECAUTIONS

In general, the sound compositions belong to the most sensitive class of firework mixtures except the hummer which consists of a black powder type composition, for example, 70% black powder in powdered state(74% potassium nitrate, 13% sulphur, 13% charcoal), 10% small grains of black powder, 20% middle flakes of aluminum (6). Therefore, careful manipulations are required in manufacturing the sound devices other than the hummer. In the table of the last page of this article, experimental results of a burning test with sound mixtures which may be used for the sound elements are shown. From the results, Whistle(4) which mainly consists of potassium picrate and potassium nitrate and Red Explosives(6) which consists of potassium chlorate and realgar are the most dangerous, however, very effective when they are safely used for the sound elements. Therefore, they have had a long life until today. There must be a suitable safe manipulation in handling even such dangerous mixtures.

5. CONCLUSION

An example of composition of a firework music following above requirements is presented in Figure 12.

Seven types of sound from fireworks could be selected as the elements of music. When these sounds are timely arranged in a rhythm in combination with the light effects, a strange effect might be obtained. The best time interval of the beats for firework music may be one second.

The most important problem is how to minimize the time deviation of the sounds from the beat interval without so much expense. It is discussed from two standpoints with time and space.

The fireworker should make effort in manufacturing sound devices to minimize the delay time deviations including the time fuse and the sound mixture. Some effective ignition materials could be used for this purpose.

The slow velocity of sound causes time deviations from beats even when the time delay of the sound devices are acculately manufactured, because most of the sound sources move with time in the air. This problem may be solved in some extent by making the maximum height of the trajectories same regardless the sizes of shells. The fireworker could manufacture the sound devices so that the beat intervals are constant at the place of the audience regulating the length of delay for the positions in the trajectory. However, when 5 or 6 inch shells are used and the maximum ascending heights are regulated to 200 meters, and the audience are more than 200 meters distant from the lifting place, there occurs no serious problem.

The deviations of the trajectory from the vertical also disturb the rhythm from the same reason above. To minimize the deviations effectively, the shells are fixed with a tail of proper length.

To harmonize the sounds to the firework lights, the shell should be manufactured so that they change the colors or lights timely with the same Rhythm. The distance of the audience from the lifting place should be 330 meters multiplied with 1/2, 1, 3/2. 2 etc.

Generally the sound mixtures are sensitive to shock or friction. A deep attention must be payed on handling.

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(3) ibid, page 277,

(4) Ellern H. Modern Pyrotechnics, page 281 (1961), Chemical Publishing Co., U. S. A.,

(5) Yamamoto S, Studies on The Safety Precautions Agaist Fire and Blind Shells in Consuming Fireworks (in Japanese), page 43(1962), Tokyo-To.

(6) ibid with (1), page 232,

(7) Dale Schafer, New Hampshire Pyrotechnic Association, Inc., Newsletter, Volume 3, Number 3, page 4(March 1991), NHPA, Inc. 6 Patten Road, Merrimack, NH 03054, U. S. A.

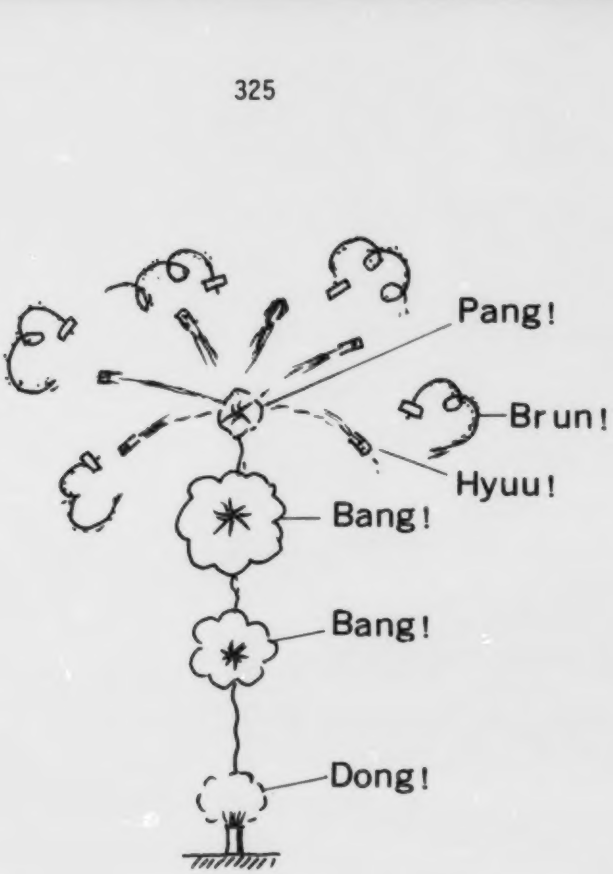
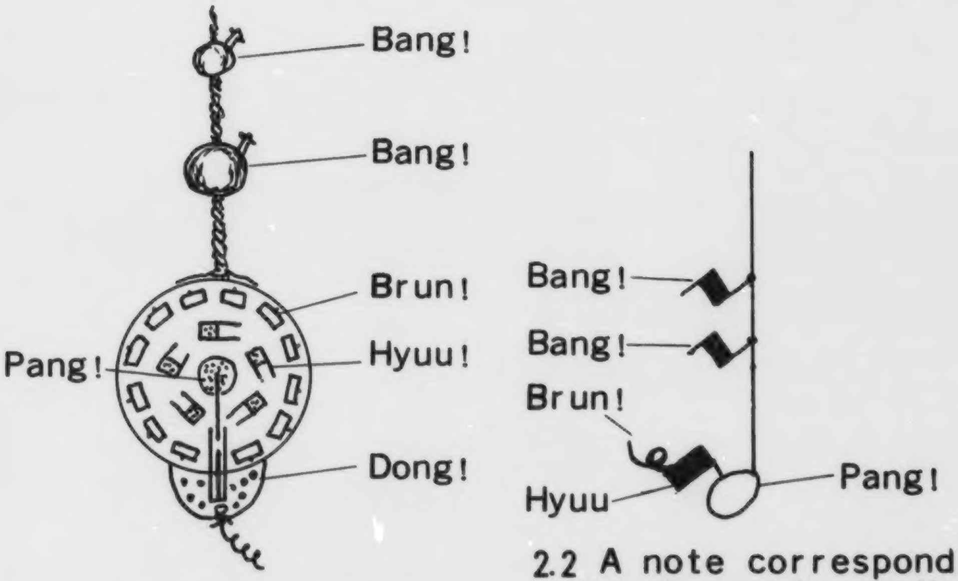

Pang!
Brun!
Hyuu!
Bang!
Bang!
Dong!

Figure 1 An example of producing sounds from a shell


Bang!
Bang!
Brun!
Pang!
Hyuu!
Dong!
Bang!
Bang!
Brun!
Hyuu
Pang!

2.1 A music shell

2.2 A note corresponding to the music shell

Figure 2 A firework music note

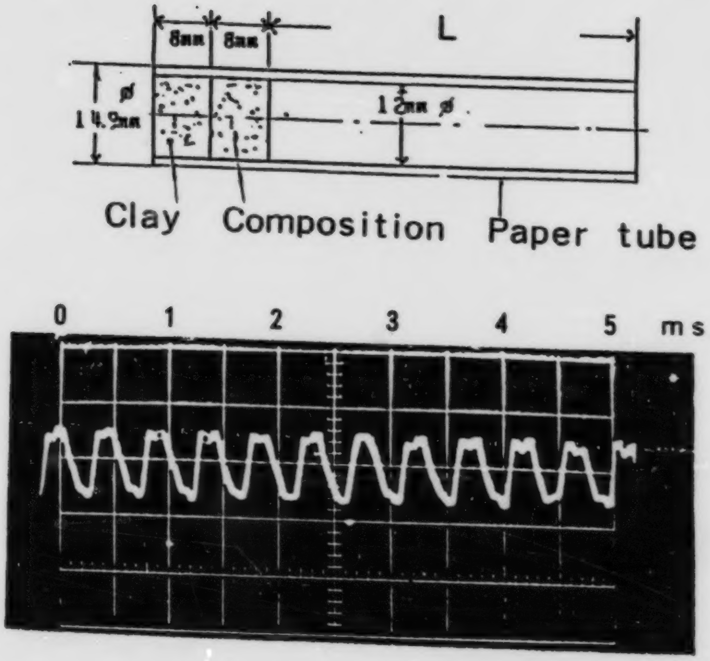

8mm
8mm
L
ø
14.9mm
12mm ø
Clay
Composition
Paper tube
0
1
2
3
4
5
ms

Figure 3 Construction of whistle(Hyuu) and the wave profile of sound

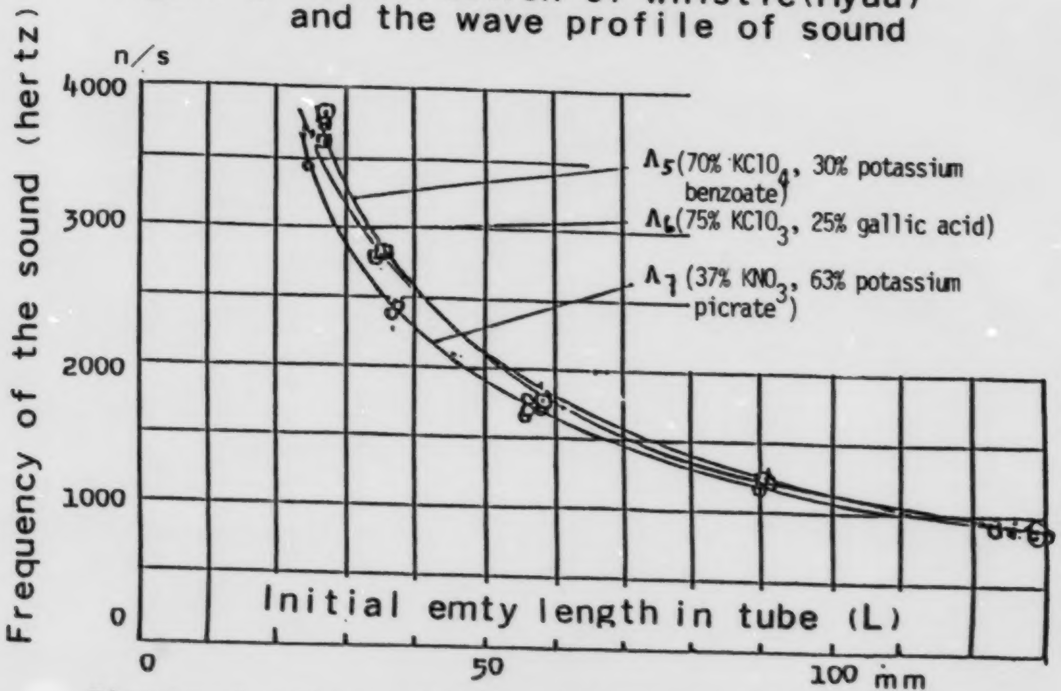


Figure 4 The relation between the frequency of the sound and the empty length in tube of whistle(Hyuu)

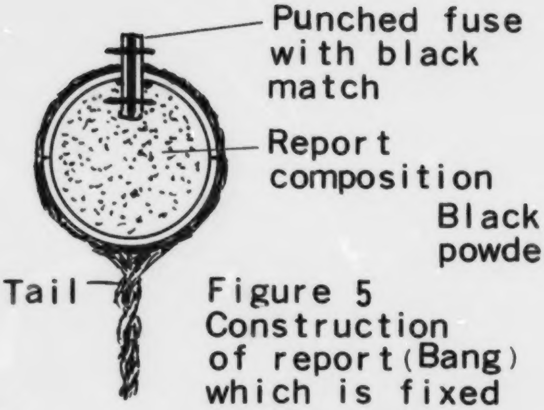

Punched fuse with black match
Report composition
Tail

Figure 5 Construction of report(Bang) which is fixed to the tail of shell

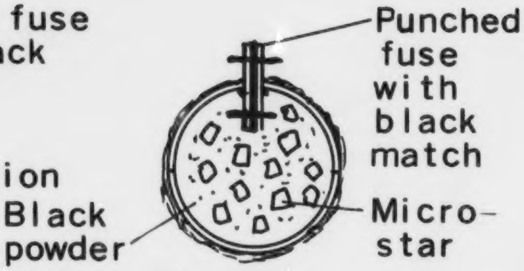

Punched fuse with black match
Black powder
Micro-star

Figure 6 Construction of small report with microstars

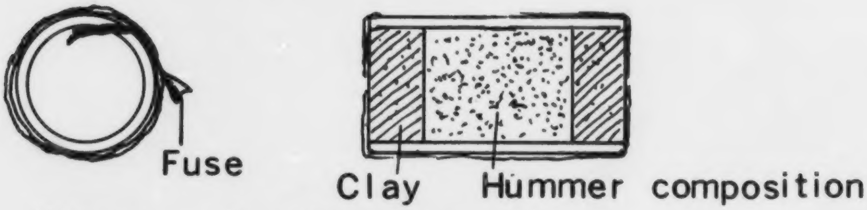

Fuse
Clay
Hummer composition

Figure 7 Construction of hummer(Brun)

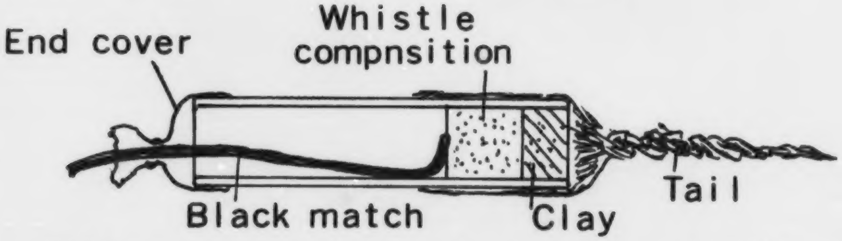

End cover
Whistle compnsition
Black match
Clay
Tail

Figure 8 Construction of whistle(Hyuu) which is fixed to the tail of shell

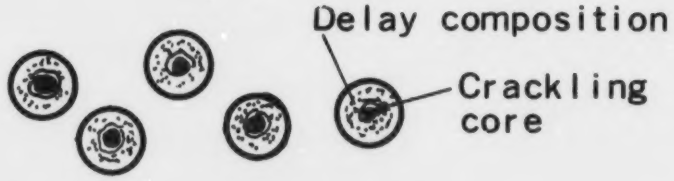
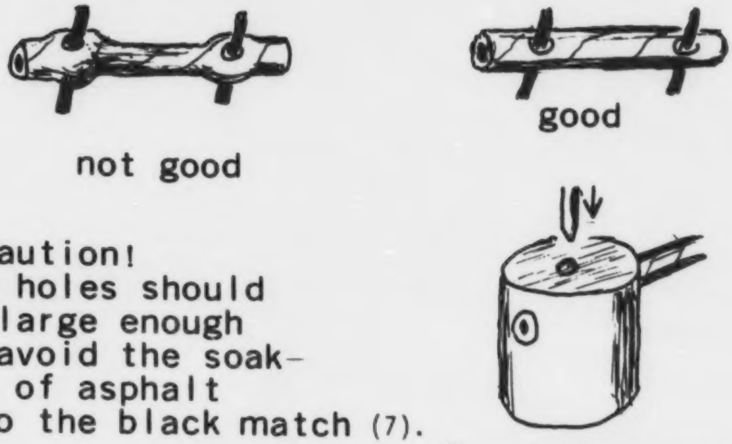

Delay composition
Crackling core

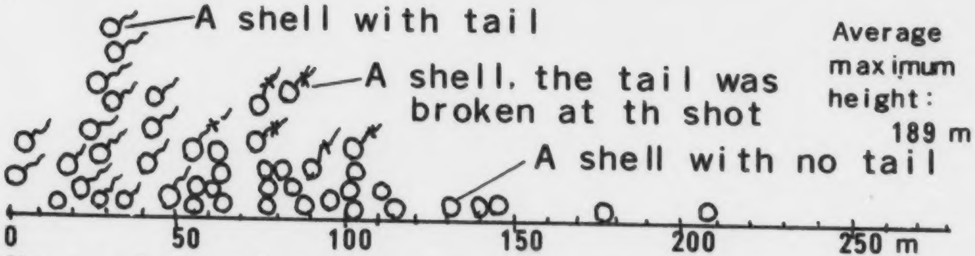
Figure 9 Microstars of cracks



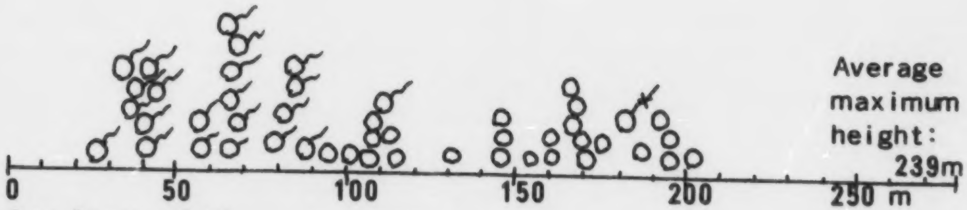
Caution!
The holes should be large enough to avoid the soaking of asphalt into the black match (7).

Punching using a form and gimlet to protect the fuse from deformation

Figure 10 Punching holes in time fuse



4.76 inch shells

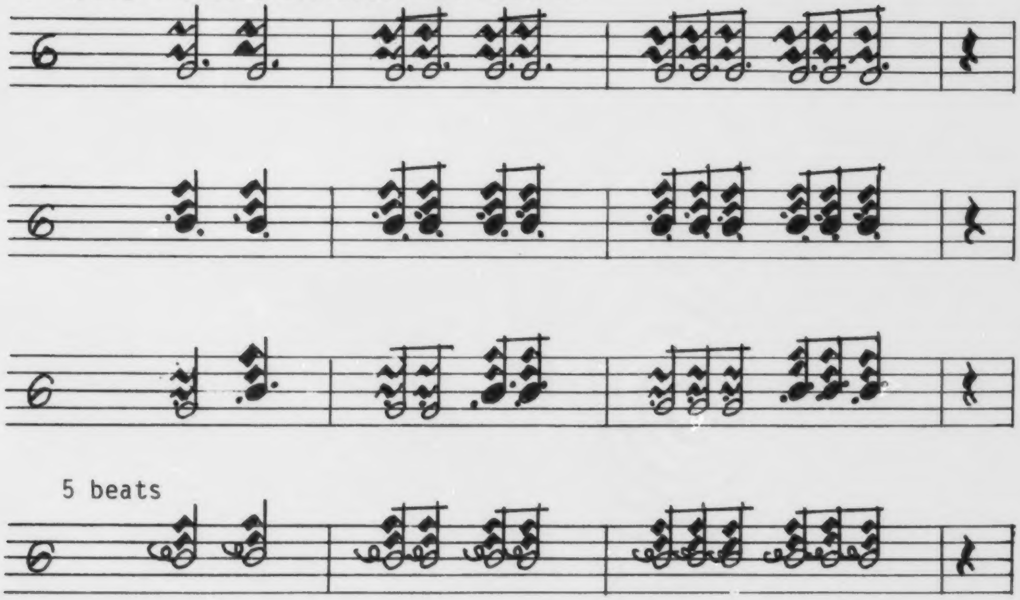


5.95 inch shells

Figure 11 An experimental results of horizontal deviations of dummy shells

Maximum average height: 200 meters

1/60, 4 beats, distance: 330 meters.



Note: Two Hyuus are generated from one tube, namely, they are replaced by one Hyuu which sounds two seconds.

1/60 : the number of beats per one minute.

4 beats : one small section consists of four beats.

330 meters: the distance between the firing position and the audience.

6: the middle line denotes 6 inch shells.

𝄽 : four beats break.

Figure 12 An example of composition of firework music

TABLE

THe burning conditions of sound mixtures in small quantity (1-2 grams) ignited by a black match

		Powder			Grains				
		unconfined	loosely in tube		unconfined	loosely in tube		pressed in tube	solid unconfined
			without lid	with lid		without lid	with lid		
Whistles:	(1) contained sodium salicylate,	B	B	B	B	B	De	B	B
	(2) contained potassium benzoate,	B	B	Q	B	B	De	B	B
	(3) contained gallic acid,	B	B	B	B	Q	Q	B	B
	(4) contained potassium picrate,	0	De	De	Q	De	De	B	Q
Report:	(5) contained aluminum,	B	De	De	B	B	Q	B	B
Red explosive:	(6) contained realgar	B	De	De	Q	De	De	De	B

Note 1: Symbols: B : burned mildly,
Q : burned quickly,
De: detonated or exploded.

Note 1: The compositions of the mixtures are as follows:

(1) 64% potassium perchlorate, 36% sodium salicylate, 2.2 add.% dextrine,

(2) 30% potassium benzoate, 70% potassium perchlorate, 3 add.% glutinous rice starch,

(3) 25% gallic acid, 75% potassium chlorate, 3 add.% glutinous rice starch,

(4) 63% potassium picrate, 36% potassium nitrate, 1% potassium perchlorate, 3 add.% glutinous rice starch,

(5) 50% potassium perchlorate, 23% fine flake aluminum, 27% antimony trisulphide, 3 add.% glutinous rice starch,

(6) 63% potassium chlorate, 37% realgar, 3 add% glutinous rice starch.

THE MONTRÉAL INTERNATIONAL FIREWORKS COMPETITION :

SIMPLY THE BEST !

By: Marc Tremblay, Assistant to the Vice President, Planning and Development.
AMARC, Ile Notre-Dame, Montréal (Québec) H3C 1A9

Summary: Created in 1985, The Montréal International Fireworks Competition has grown into the largest fireworks competition in the world. Each year, the world's major fireworks firms come to Montréal and present a 30-minute pyro-musical show at La Ronde.

The Competition is notable both for the number of competitors who participate (an average of seven per year) and for its international dimension (some 30 firms representing 17 countries have competed since 1985).

Participants benefit from an exceptional site on which to stage their fireworks displays, with three launching pads nestled between the St. Lawrence River and Lac des Dauphins. AMARC, which produces the Competition, also provides competitors with the most up-to-date facilities as well as the expertise of a technical team well-acquainted with the site's limits and potential.

Each year the Competition attracts an average of 1.5 million spectators, generating significant cultural and economic spin-off for Montréal as well as contributing in its own special way to the development of the art of fireworks. In the words of Giovanni Panzera, the Competition's artistic director, Montréal has become the "University of Fireworks", a laboratory where companies can innovate and stretch the limits of fireworks design and showmanship.

Résumé : Créé en 1985, le Concours international d'art pyrotechnique de Montréal est devenu la plus importante compétition de feux d'artifice au monde. Le Concours réunit chaque année à La Ronde (Montréal) les plus grandes firmes pyrotechniques qui viennent y présenter un spectacle pyromusical d'une durée de 30 minutes.

Le Concours se distingue par le nombre de concurrents en lice chaque année (en moyenne sept) et par sa dimension internationale alors que 30 firmes représentant 17 pays ont concourru depuis 1985.

Les participants bénéficient d'une scène exceptionnelle avec trois rampes de tir nichées entre le fleuve et un lac. L'AMARC, producteur du Concours, met également à la disposition des concurrents des installations des plus modernes ainsi que l'expertise d'une équipe technique au fait des contraintes et du potentiel du site.

Le Concours, qui attire chaque année une moyenne de 1,5 million de spectateurs, a des retombées culturelles et économiques très importantes pour Montréal en plus de contribuer de façon toute particulière au développement de l'art pyrotechnique. Selon les paroles mêmes du directeur artistique du Concours, Giovanni Panzera, Montréal est "l'université des feux d'artifice", un laboratoire où les firmes peuvent innover et se dépasser dans la conception d'un spectacle pyrotechnique.

Montréal, June 2, 1989, 8:00 p.m. - The Jacques-Cartier bridge, which links the Island of Montréal to the South Shore, is closed to traffic. Crowds of excited spectators have poured into La Ronde and out onto the bridge deck in order to have ring-side seats for the show: a 30 minute pyro-musical display designed by Pirotecnia Caballer and presented as part of the Montréal International Fireworks Competition. In the crowd, an attentive spectator: Syd Howard, Australian leader in the field of fireworks production and display. His firm has applied to join the 1990 edition of the competition and he has come to view the display and to answer Giovanni Panzera's fateful question: "Can you do better?"

His answer will determine whether or not his firm's application is accepted, since only those companies capable of presenting a 30-minute fireworks display that meets the Competition's rigorous standards will be accepted. Needless to say, the number of firms that qualify is small. This is precisely the trademark of the Competition: to assemble the world's best pyrotechnists in Montréal.

In other words, all the competitors are leaders in the fireworks field in their respective countries. Indeed, over the years, the Competition has had the honour of welcoming such prestigious firms as the Société Étienne Lacroix from France, Pirotecnia Igual - a Spanish firm, Lünig Feuewerk Stuttgart from Germany and the venerable Marutamaya Ogatsu from Japan, to name but a few.

Historical Background

The Montréal International Fireworks Competition was created in 1985. The Association montréalaise d'action récréative et culturelle (AMARC), a para-municipal Montréal corporation, was then looking for an original way to kick off the season at La Ronde, Québec's largest tourist attraction.

In order to stage such a large-scale event, AMARC began looking for a major partner; Rothmans, Benson & Hedges Inc. decided to accept the challenge and the Benson & Hedges Inc. International was born.

The Competition was an instant smash success, with more than 5.7 million spectators attending the inaugural edition. This figure constitutes an absolute record in Canada for this type of event. As a result of this phenomenal response, organizers decided to repeat the experience each year.

In the beginning, the Competition included two types of shows: traditional, so-called "classic" fireworks shows, and pyro-musical displays, which involve carefully synchronizing fireworks explosions with a musical score. Since 1987, the displays have been exclusively pyro-musical, which experts consider to be the last word in fireworks.

Starting with the second edition of the Competition, the Benson & Hedges Inc. International hired the services of Giovanni Panzera, first as a consultant and then as artistic director for the Competition. Mr. Panzera brought with him a vast experience in the field. Initiator of the first musical fireworks displays in Europe and one of the organizers of the Cannes Fireworks Competition from 1973 to 1983, he developed the Roman candle and set up Industria Pirotecnica Panzera, a company which presents hundreds of fireworks displays each year. Mr. Panzera's artistic sense and in-depth knowledge of the milieu have enabled him to set the tone for the Competition and to play an important role in its success. Each year, he has the honour of presenting the final fireworks display of the Competition and all those who have seen his displays are unanimous in acknowledging that they reflect the work of a master pyrotechnist: an artist who devotes all his talents to the production of fireworks shows.

The Benson & Hedges Inc. International is also noteworthy because of its international dimension. During the past seven editions of the Competition, spectators have enjoyed presentations from representatives of 17 countries spread over five continents: Europe, Asia, Australia, North America and South America. In all, 30 different firms have participated in the Competition, presenting a total of 53 fireworks displays!

One might worry that Montréalers would become somewhat blasé after all these presentations. On the contrary! Year in, year out an average of 1.5 million Montréalers gather together at La Ronde, on the bridge or on either side of the river to enjoy this unique spectacle. Moreover, Montréalers have become one of the most informed publics in the world when it comes to fireworks and appreciate the efforts of the pyrotechnists for their true value. Indeed, in Montréal, pyrotechnists become the true stars of the evening; normally speaking, they are accustomed to playing a backup role at festivities in their native countries. Montréalers welcome pyrotechnists in their own right and treat them as artists rather than explosives technicians.

The Formula

Each year, from the end of May to the end of June, the Benson & Hedges Inc. International presents an average of eight pyro-musicals, including a closing show that is not part of the Competition.

Because of the number of participants that take part in this Competition, it is the largest of its kind in the world. The participants defend the colours of their respective countries and their presentation is judged by a six-person jury, based on the following criteria:

- pyro-musical design: quality and originality of the firework and sound components
- sound: quality and originality of the sound track and quality of the recording
- synchronization: accuracy with respect to simultaneity of sound effects and firework components.

The jury, which is selected by AMARC, awards Gold, Silver and Bronze Jupiter trophies, as well as a Jupiter for the best musical score. These Jupiter have quickly become symbols of prestige within the fireworks industry, as well as unrivalled signs of recognition for the winners.

The Site and the Facilities

The site chosen for the Benson & Hedges Inc. International is exceptional, with three launching pads located between the banks of St. Lawrence River and Lac des Dauphins (see Figure 1). This lay-out allows the participants to design complex configurations by combining different effects and different levels.

Launching pad No. 1, located on the banks of the St. Lawrence, can be used for large-calibre devices (maximum 305 mm). These devices can be directed toward the river, thus ensuring the safety of the audience. The second pad is at the edge of La Ronde, near Lac des Dauphins. Here, the entire range of medium-sized fireworks can be launched (maximum 105 mm), namely rockets, flying saucers and gerbes.

The third launching pad, located on Lac des Dauphins itself, is made of floating platforms. It is used for candles, fountains, nautical components and small special-effect components. All of these ground-level effects are greatly enhanced thanks to the mirror image provided by Lac des Dauphins.

An electrical ignition system has been permanently installed on the launching pads. Ignition is controlled from Place d'Animation using a console equipped to handle up to 200 ignitions. The console is linked by underground cable to two electrical connection boxes located on Pads 1 and 2.

In order to ensure top-quality sound reproduction for the show, AMARC has installed 32 acoustic loudspeakers around the lake. The amplification system boasts a total power rating of 40,000 watts. Moreover, all of the sound tracks used by the participants are converted to digital recordings for use on Digital Audio Tape Recorders.

The grandstands around Lac des Dauphins provide a comfortable environment for the audience to attend the 30-minute show. Some 7,000 reserved seats (as well as standing-room for 30,000) are available each evening that the fireworks are presented.

Conditions For Participation

Based on advice from Giovanni Panzera, AMARC first invites a number of pyrotechnical firms to submit applications. Candidates are then evaluated by Mr. Panzera and the AMARC team, who also take into account advice from Energy, Mines and Resources Canada. Once a firm's application has been accepted, AMARC swings into action on a number of fronts. In fact, the preparations to produce the eight 30-minute shows take more than a year to complete.

Before participating, each firm must come to Montréal and attend one or more pyro-musical presentations, in order to become familiar with all the prerequisites for presenting a fireworks display at the Competition. In the months that follow, Mr. Panzera keeps in touch with the candidates to help them develop their launching scenario.

During that time, AMARC plans for the maritime transportation of all the pyrotechnical material. AMARC assumes the cost of such transportation and ensures that all customs formalities are taken care of.

AMARC also obtains import permits for any components that do not conform to the requirements of the Explosives Division of Energy, Mines and Resources Canada. Because AMARC has always scrupulously respected the safety rules set out by this Division, it has never experienced any regrettable incidents during the Competition. Moreover, on the evenings of the fireworks displays, some 500 police and fire-fighters are always on hand.

Although the invited firms receive a lump sum to produce their 30-minute show, many of the competitors also dig into their own pockets to ensure that the audience and ... the jury enjoy their fireworks display. It is estimated that competitors launch an average of 3,500 components at the Montréal Competition, but there has been shows where more than 5,000 components of all types were launched.

Once in Montréal, the invited firms have five days to set up their show, that is, two days for pre-staging and three days for staging (on the launching pads). AMARC assumes the cost of travel, as well as lodging for five people during this period. To help competitors in their work, AMARC provides the services of a 14-person team comprised of a technical coordinator, five fireworks experts, two foremen and six workers.

During the show, a stage manager, assistant stage manager, sound technician and ignition system director are on duty.

The Competition's artistic director, Giovanni Panzera, is also on hand to advise the firms, if necessary, on how to maximize the desired effects and deal with the prevailing winds.

It should be pointed out that in seven years of competition there have been no show cancellations due to the weather or other reasons.

After seven years on the job, the technical team is well aware of the site's potential and limitations and passes this expertise on to the invited firms. The physical facilities have also been improved over the years to meet the needs of the participants while maintaining the high standards required for the Competition.

Spin-offs

Holding the Benson & Hedges Inc. International in Montréal for the past seven years has produced spin-offs on several levels.

First, the Competition has made a unique contribution to developing the art of fireworks displays. Montréal quickly became known as a place to experiment, a laboratory so to speak, in which companies can innovate and stretch the limits of firework design and showmanship.

According to Giovanni Panzera, Montréal has become a "University of Fireworks" and has carved out a position at the cutting edge of pyrotechnical research.

The increasingly elaborate interaction between sound and visual effects is a good example of such experimentation. A number of shows have been based on such an interactive approach; the most striking example, however, was undoubtedly the pyro-animation display put on by the Dutch firm JNS Pyrotechnieck in 1991. The launching of the various components punctuated and accentuated the action of a film projected onto a giant screen.

The presentation of a series of unconnected scenes increasingly gave way to an overall concept where dramatic progression plays an important role. This was the case with the presentation made by Pyro Spectaculars Northwest in 1990. In this instance, American Eric Tucker based his performance entirely on the sound track of Les Misérables. He played on a wide range of emotions, often to an unequalled degree of intensity. Giovanni Panzera tried something similar in 1987, using Ravel's Bolero. The audience was able to see that the quality of a show is not measured in decibels but, like a painting, by the subtlety and richness of its composition.

The Benson & Hedges Inc. International also allowed firms to experiment with new musical scores. Rock'n roll, Philip Glass's minimalist music and even electronic music have been added to the traditional classics and film soundtracks. In 1990, the Artistes Associés Suisses even incorporated cow bells and the sound of cuckoos into their musical score!

Another interesting spin-off of the Competition is the expertise developed by the AMARC team. This expertise has allowed pyrotechnists to use the launching pads at Lac des Dauphins as a training ground. Some were even bitten by the bug and carried the adventure a little further. For example, the Montréal firm Fiatlux was born out of this experience.

This expertise also resulted in the creation, jointly with CANMET, of the current International Symposium on Fireworks, an experience that will both enrich the Competition and keep it in the forefront of the art of pyrotechnics.

Finally, the most immediate impact from this Competition can be measured within the Montréal community. The contribution made by such an event to the cultural life of the city is enormous. Each year, Montréalers see the very best pyrotechnists in the world at work. It is impossible to put a price tag on such a unique event.

On the other hand, it is possible to measure the Competition's impact on Montréal's economy, which has been significant. In fact, a study undertaken by AMARC estimates that the spin-offs from the Benson & Hedges Inc. International will range in excess of $90 million from 1990 to 1995.

This amount includes AMARC's expenses and money spent by spectators, especially tourists, during the Competition. To this must be added other spin-offs such as the increased influence and visibility for Montréal on the international scene.

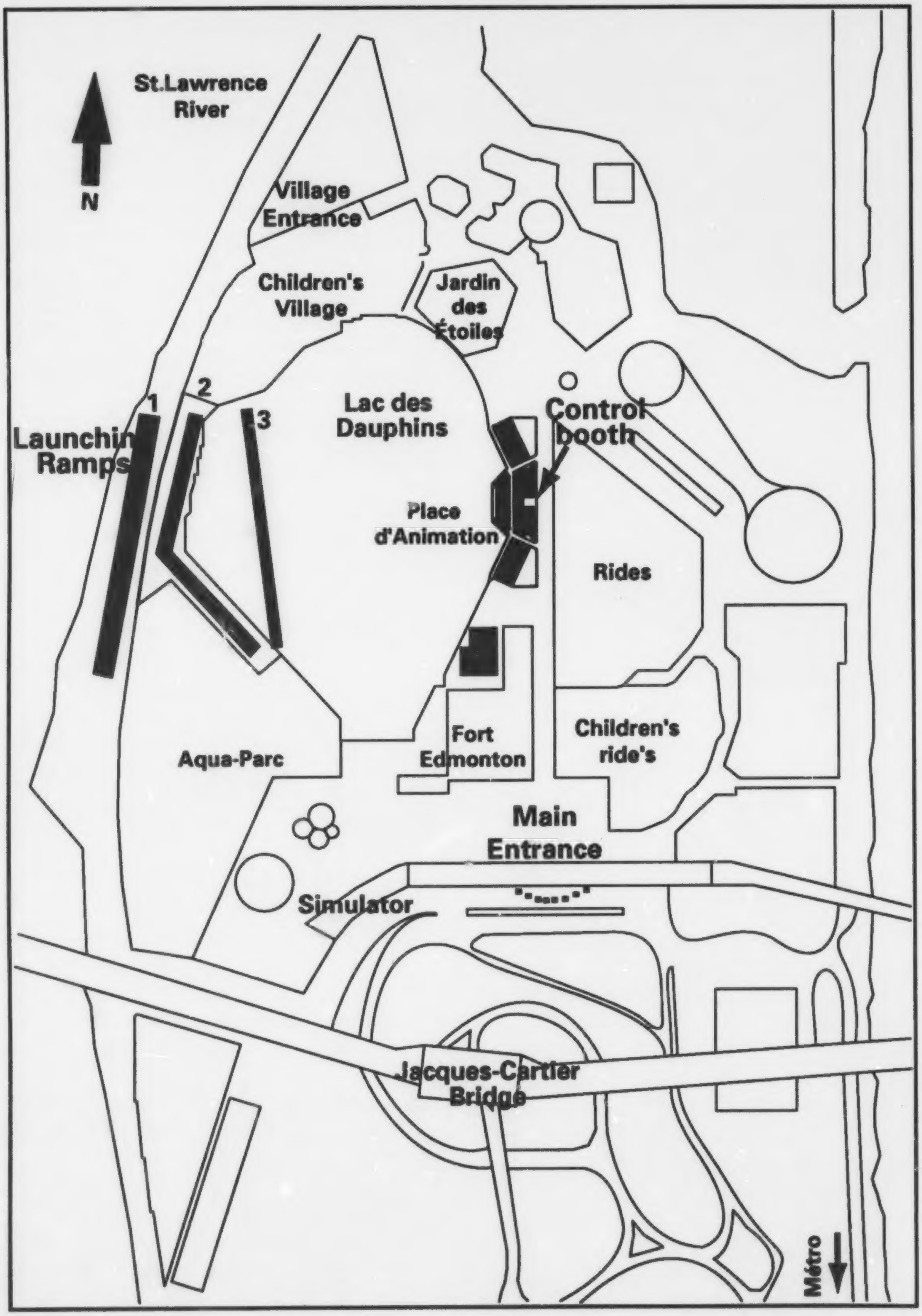
We should also point out that the Benson & Hedges Inc. International is largely a self-financing event, thanks to the collaboration of numerous partners from the private sector, in particular Rothmans, Benson & Hedges Inc.

1992: A Special Edition!

In 1992, the City of Montréal is celebrating its 350th anniversary, while La Ronde marks its 25th birthday. The Benson & Hedges Inc. International plans to highlight this double anniversary with a special edition of the Competition. A record number of pyro-musical fireworks will be presented from the end of May to the beginning of August. The calibre of competition should be especially high this year, with the return of a number of former Gold Jupiter prizewinners. And for an added twist, winners will be chosen by a jury made up of the public at large.

Consequently, the 8th edition promises to be most memorable; moreover, it will carry on the Competition's tradition of creating innovative approaches to fireworks displays. Indeed, if the Benson & Hedges Inc. International is to maintain its reputation for excellence and prestige, the AMARC team has no time to rest on its laurels; this is why it is constantly searching for new ways to stimulate the competitors and keep the public in suspense. The challenge? Stretch the limits of pyro-musical art and perfect our mastery of fire.

Illustration 1


St.Lawrence River
N
Village Entrance
Children's Village
Jardin des Étoiles
1
2
3
Launching Ramps
Lac des Dauphins
Control booth
Place d'Animation
Rides
Fort Edmonton
Children's ride's
Aqua-Parc
Main Entrance
Simulator
Jacques-Cartier Bridge
Métro

Map of La Ronde
Host of the Benson & Hedges Inc. International
Montréal, Canada

TRAM

OBSERVATIONS ON THE SENSITIVENESS AND REACTIVITY OF CERTAIN PYROTECHNIC MIXES THAT HAVE BEEN INVOLVED IN IGNITION ACCIDENTS

by

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ABSTRACT

The Health and Safety Executive's laboratory at Buxton has investigated a number of accidental ignitions that have occurred with pyrotechnic compositions. In this paper, results relating to compositions containing potassium chlorate/thiourea, and titanium/blackpowder are presented and discussed. Our studies have concentrated primarily on an evaluation of the mechanical sensitiveness, and in some cases thermal properties, of these mixtures and show that the fuel-oxidiser combinations are substantially more sensitive to both impact and friction than the constituents.

The data obtained with potassium chlorate/thiourea indicate that certain S-containing compounds could present a hazard when present in admixtures with potassium chlorate that is similar in magnitude to that previously documented for free sulphur.

With titanium/blackpowder mixtures, we have shown that, although the mechanical sensitiveness is not dependent on the particle size of the titanium (over the range investigated) it is highly dependent on the proportion of titanium present in the mix. The form of the dependence of the friction and impact sensitiveness on titanium content differs, with the friction data indicating a maximum sensitiveness for mixtures containing 20 - 30% titanium.

Full technical details of these investigations will be published elsewhere: the purpose of the present summary paper is to provide early notification of these observations.

INTRODUCTION

One of the roles of the Commercial Explosives Section of the Health and Safety Executive's Explosion and Flame Laboratory lies in investigating the technical aspects of accidents involving explosives. A significant number of investigations undertaken in recent years have involved pyrotechnics, and the present paper examines studies in two areas that have provided useful information relating to safety in the handling of these materials.

The properties of pyrotechnic mixtures are difficult to predict and it is known, for example, that individual pyrotechnic compositions can be found throughout the explosiveness/sensitiveness plane (1). It is because of this uncertainty that detailed investigations of the type reported in this paper were deemed necessary.

Full technical details of the incidents and our investigative work will be published elsewhere (2,3). Rather than providing an in depth report of the studies, the purpose of the present paper is to give early notification of the safety implications of our findings to the industry.

COMPOSITIONS CONTAINING POTASSIUM CHLORATE AND THIOUREA

An explosion occurred during the operation of a grinder that had been used to process potassium chlorate and then thiourea without being cleaned out in between. Although in this case the potassium chlorate/thiourea mixture was not formed deliberately, this type of mix is used in the production of white smokes (4).

We were unable to locate any useful information in the literature relating to the reactivity of this mixture; our studies therefore examined the mechanical sensitiveness of mixes made up from industrial samples and containing 15, 20 and 25% thiourea. The tests used were UN (5) methods 3a (iii) for impact (the Rotter test) and 3b (ii) for friction (the Rotary Friction test). Values for Figures of Insensitiveness, and Figures of Friction were evaluated by reference to the performance of the explosive RDX, in accordance with standard procedures.

Mixtures were well mixed and shaken vigorously prior to extraction of samples for test. The Rotter impact results indicated that the Figure of Insensitiveness (evaluated by comparison to the explosive RDX which has FOI = 80) could only be determined for the mixture containing 15% thiourea, when a value of 23 was obtained. Mixtures with 20 and 25% of the thiourea constituent were found to be too sensitive to yield a result.

For both potassium chlorate and thiourea tested individually, there were no fires from the maximum drop height.

The Rotary Friction test employing the standard test condition of 40 psi indicated that all three mixtures were too sensitive to yield a numerical result. Testing with a reduced pressure of 5 psi, in accordance with the procedure recommended by the Sensitiveness Collaboration Committee of the UK Ministry of Defence (1), produced results for Figures of Friction of 0.3 for the 15% mixture and 0.4 for both the other mixtures (containing 20 and 25% thiourea).

Whereas the impact results indicate that, individually, both potassium chlorate and thiourea would be judged to be "comparatively insensitive" by the SCC criteria, mixtures of these materials displayed a significant increase in sensitiveness. The

15% mixture would be classed as "very sensitive", whereas those containing 20 and 25% thiourea were too sensitive for a determination to be made.

Similarly for friction, the fuel-oxidiser mix was shown to be substantially more sensitive than either of the constituents. All the mixtures would be classed as "very sensitive", whereas thiourea alone was too insensitive to give a result and potassium chlorate gave a FOF of 4.1, resulting in the assignment "sensitive".

Temperatures of Ignition for the three mixtures were determined using the SCC method (1) which employs a heating rate of 5°C min^{-1}. Tests were done in duplicate and yielded results in the range 142.3 - 153.3°C, indicating that there is a possibility of ignition of any of the mixtures at less than 155°C, a temperature which is 200°C lower than the melting point of the oxidiser (6). Both thiourea and potassium chlorate when tested alone gave no ignitions below 400°C.

In general agreement with these results, DSC tests showed strong exotherms at around 160°C with high reaction energies (in excess of 2000 J g^{-1}). The UN scheme (7) considers materials to be self reactive (ie. energetic) if they decompose at relatively low temperatures and exhibit transition energies greater than 300 J g^{-1}. The measured values are well in excess of this threshold.

The DSC results for tests with the individual components indicated that potassium chlorate undergoes no reaction up to about 300°C, and that thiourea displays only an endotherm attributed to melting at about 168°C. In agreement with the observations of sensitiveness, the oxidiser/fuel mixes were again seen to be significantly more reactive than either of the components.

In the UK, the use of admixtures of sulphur and potassium chlorate in fireworks is prohibited by Order in Council No. 15 on the grounds that they "are not only liable to spontaneous ignition, but tend to become exceedingly sensitive to ignition by friction or percussion" (8).

The thermograms of the potassium chlorate/sulphur system give an indication of this reactivity, showing a violent ignition reaction below 150°C ie. 200°C below the melting point of the oxidiser. Similarly, our results show that mixtures of potassium chlorate with the S-containing compound thiourea are sensitive to impact and friction, and that they also react at relatively low temperatures.

The ignition temperature and the burning rate of high-energy mixtures are both determined by a number of factors, one of which is the need for the oxidiser or fuel to be present in the liquid state. It is for this reason that a substantial lowering of the ignition temperature of many compositions has been reported when they contain low melting point fuels. Sulphur, which melts at 119°C and exhibits ring fragmentation at temperatures above 140°C, is clearly in this category. Our studies have now shown that thiourea may behave similarly.

Diffusion of a liquid fuel into a solid oxidiser will occur if there is sufficient amplitude of vibration within the ionic crystal. The extent of motion within the lattice can be somewhat quantified by reference to the Tammann temperature which is defined as 0.5T where T is the melting point in °K. At this temperature the solid has about 70% of the vibrational freedom present at the melting point and diffusion within the crystalline lattice becomes significant.

Potassium chlorate has a Tammann temperature of only 42°C ie. well below the melting point of 356°C, indicating that there should be significant diffusion of mobile species into the lattice at temperatures well below the melting point. This increases the likelihood of chemical reaction between the oxidiser and the fuel at relatively low temperatures.

These observations may explain, at least in part, the history of accidental ignitions with compositions containing potassium chlorate since a relatively small mechanical stimulus would be required to produce localised heating in the composition to temperatures in excess of the Tammann temperature.

Since the thermal decomposition of potassium chlorate is an exothermic process, once reaction is underway heat is released both by the oxidation process and by decomposition of the oxidiser, causing an acceleration in reaction rate.

COMPOSITIONS CONTAINING TITANIUM AND BLACKPOWDER

Following two ignitions during the consolidation of titanium/blackpowder mixtures of the type commonly used in the manufacture of display gerbs, we investigated the impact and friction sensitiveness of this composition in some detail.

Initial results were reported in 1991 (9). The work has now been completed and full details will be published elsewhere (3).

In our studies we examined the effect of the particle size and proportion of titanium on the mechanical sensitiveness of the titanium/blackpowder mix. The materials employed were supplied by a major fireworks manufacturer in the UK : the results therefore relate to the practical problems that can encountered when working with compositions of this type.

We used the same standard UN sensitiveness test methods as in the potassium chlorate/thiourea study reported above.

Titanium flake (10-20 mesh) was sieved and mixtures with blackpowder meal A were made up using the fractions with particle sizes in the ranges 355- 500 μm and 710 - 1000 μm.

Although mixtures of titanium/blackpowder containing up to 30% titanium are commonly used in the industry, we extended our investigations to cover compositions with up to 70% titanium in order to accurately evaluate the form of the dependence of sensitiveness on titanium content and because it was felt that localised higher concentrations of titanium could occur if poor mixing of the composition had occurred.

Some numerical results have previously been reported (9), but Figures 1 and 2 summarise the findings from our completed study of impact and friction sensitiveness, respectively.

The impact results indicate that mixtures of titanium and blackpowder become increasingly sensitive as the proportion of titanium increases. Mixtures containing more than approximately 20% titanium would be judged to be "sensitive" to impact stimuli using the SCC definitions. Figure 1 also illustrates that the particle size of the titanium does not exert an effect over the range of sizes examined in our studies.

The data obtained for friction sensitiveness illustrate a different form a dependence to that found for impact. The dependence of FOF on the proportion of titanium in the mixture passes through an area of maximum sensitiveness for mixtures containing 20 - 30% titanium. It is noted that mixtures commonly used in the fireworks industry often contain quantities of titanium in this range.

Using the SCC definitions to allocate relative sensitiveness to the values obtained, it is seen that the titanium/blackpowder compositions containing ca. 3-75% of titanium would be judged to be "sensitive". Mixtures with titanium present in the proportion 20-30% are almost in the "very sensitive" category.

Again, it was observed that the particle size of the titanium exerted no effect on sensitiveness over the range studied.

The results of our work show that adding small proportions of titanium (less than 5%) to blackpowder can cause the sensitiveness to alter from "comparatively insensitive" to "sensitive". This observation, and the previously reported identification of friction as the most common source of ignition accidents involving pyrotechnics (10), may provide some explanation for the occurrence of the two incidents involving titanium/blackpowder mixes.

CONCLUSIONS

The studies reported in this paper were undertaken in response to the occurrence of incidents, and serve to illustrate the importance of obtaining basic information relating to the sensitiveness of pyrotechnic mixtures.

Although the use of thiourea/chlorate mixtures is not particularly widespread in the industry, our studies have identified that enhanced reactivity of the type previously documented for the free sulphur/chlorate system could also be found with mixtures of potassium chlorate and organic fuels containing chemically bound sulphur.

For mixtures of titanium and blackpowder we have shown that compositions containing 20-30% titanium by weight are particularly friction sensitive. Since this represents a common mix in gerb production, industry may wish to examine both the types of working procedures used in processing such mixtures, and the suitability of other less sensitive mixtures of the same ingredients.

ACKNOWLEDGEMENTS

The author is grateful to past and present members of Commercial Explosives Section for producing the experimental results that form the basis of this paper particularly Mr A J Barratt, Mr J A Harding and Mr R J Rapley.

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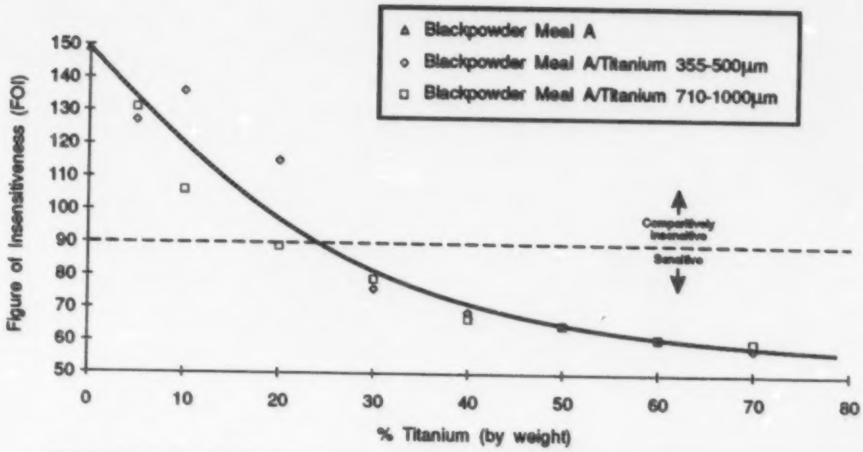

Figure 1: ***The Impact Sensitiveness of Blackpowder/Titanium Mixes***

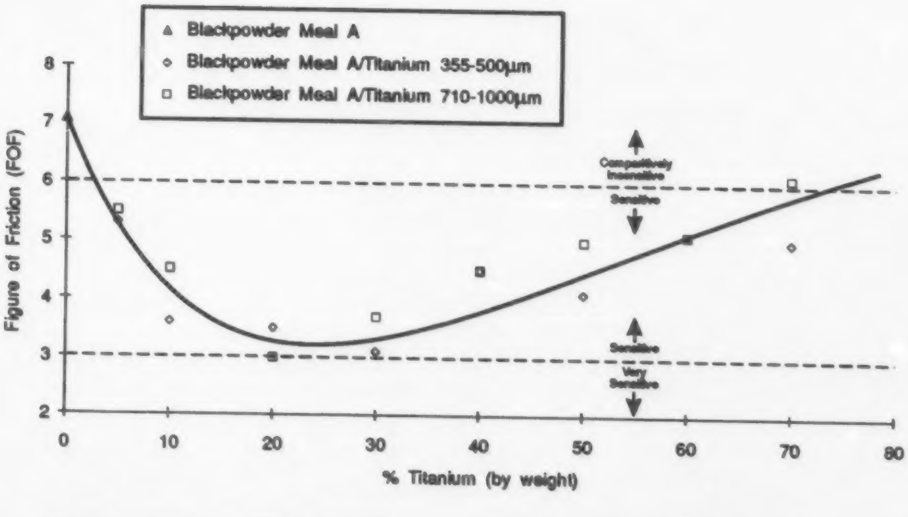

Figure 2: ***The Friction Sensitiveness of Blackpowder/Titanium Mixes***

FUNDAMENTALS OF FIRE AND EXPLOSION HAZARDS RECOGNITION AND CONTROL IN FIREWORKS MANUFACTURING

Electrostatics

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Abstract

Highly energetic materials, such as pyrotechnics, are designed and manufactured to serve many functions, and they are intended to decompose rapidly and controllably with an attendant release of energy. The activation energy needed to initiate the decomposition of pyrotechnics can be provided by several sources. It is when these potential sources of activation energy are uncontrolled or unabated in the manufacture of pyrotechnics at fireworks plants, that accidents occur. This paper, which is the first in a planned series of papers on sources of accidental ignition of pyrotechnics, deals with electrostatic ignition. The paper is divided into three main sections. The first section addresses the nature and characteristics of electrostatic charges, including their generation, accumulation and dissipation. The second section presents examples of electrostatic calculations which are germane to static electricity hazards in the fireworks industry. The third section provides guidance on the control of electrostatic hazards.

ELECTROSTATIC IGNITION SOURCES

Static electricity is a well known phenomenon. Anyone who has slid across a vinyl automobile seat or walked across a floor and received a shock when touching a door handle or knob or has seen the miniature lightning and heard the crackling noise when removing a garment, is familiar with electrostatic discharges. In each case the process involved the generation, accumulation and finally the rapid dissipation through a spark of an electrostatic charge.

Despite considerable efforts to control inadvertent electrostatic ignitions of flammable gases, vapors, dusts and energetic materials, serious fires and explosions due to static ignitions continue to plague the chemical process industries. Certainly included in this group is the fireworks industry.

The petroleum industry, using processing equipment made of metal and other suitably conductive materials, together with attention paid to bonding and grounding practices, has controlled well if not eliminated the development of static ignition sources. Industries working with energetic materials (pyrotechnics, explosives and propellants) have for safety reasons used some processing equipment constructed wholly or in large part of non-metallic materials. Whereas the replacement of metal equipment or components with ones made of non-metals may reduce compression and friction ignition hazards and the threat of metal fragmentation from equipment explosions, the use of non-metals, which are often non-conductors, increases the possibility of electrostatic ignitions. At fireworks plants throughout the U.S., non-metallic materials, such as paper, cardboard, wood and an ever increasing amount of plastics, are used in the production and handling of pyrotechnics. While usually none of the materials commonly used in the fireworks plants pose a significant electrostatic ignition hazard, under certain conditions , such as low relative humidity, they might.

In this section, the nature and characteristics of static charges, their generation, accumulation and dissipation will be presented. The general references are (1-11).

Background

When an electrical charge is present on the surface of a nonconductive body (insulator), where it is prevented from escaping, it is called static electricity. An electrical charge present on a conductive body which is only in contact with nonconductors is also prevented from escaping and is also immobile or static. In either case, the body on which the static electricity resides is said to be "charged."

The generation of static electricity is not in itself an ignition hazard. The hazard arises when electrostatic charges accumulate and subsequently discharge as an incendive spark across an air gap in the presence of highly flammable material. If an electrostatic charge is to be an ignition source, four conditions must be met.

1. There must be a mechanism for charge generation.
2. There must be a means of accumulating charge and maintaining an adequate electrical potential.
3. There must be a discharge spark of adequate energy.
4. The spark must occur in an ignitable medium.

A static charge may be generated as the result of physically separating or pulling apart contacting surfaces of dissimilar materials. One or both of the materials must be a poor electrical conductor (insulator) and the materials can be either solids or liquids. Charge generated by this mechanism is commonly referred to as separation, frictional or triboelectrical charging.

A charge may appear on the surface of an object as a result of being brought close to another electrostatically charged object. This charging mechanism is called "induction." Another mechanism for surface charging involves "bombardment" with charged air molecules (ions) which themselves have become charged by collisions with electrons within a high-voltage corona. Surfaces under vacuum and subjected to an electron beam will also acquire an electrostatic charge, a process known as "charge injection". Charge injection is the underlying phenomenon responsible for the generation of the electrostatic charge which resides on the outside viewing surface of an energized cathode ray tube, e.g., a television or computer monitor screen.

An initially neutral (uncharged) surface may become charged through direct contact with another charged surface.

Because its intrinsic origins are present at every interface, the generation of static electricity cannot be prevented completely. The object of most static-corrective measures is to provide a means whereby charges separated by whatever cause may recombine harmlessly before sparking potentials are obtained, or to avoid spark gaps where harmful discharges could occur. If hazardous static conditions cannot be avoided in certain operations, means must be taken to assure that there are no ignitable substances at points where sparks may occur.

Some electrical terms frequently used in the science of electrostatics are defined below. The definitions have been taken with editing from the references cited.

Capacitance. Measured in farads or fractions thereof. Capacitance is something like a tank of air. Each ounce of air pumped into the tank raises the pressure in the tank a certain amount. This amount is determined by the size or capacity of the tank. In a tiny tank the pressure rise is large when a fixed amount of air is introduced. In a large tank the pressure rise is small when the same amount of air is added. Naturally the air will remain in the tank until someone opens the valve to let it out or until the tank bursts.

To say this same thing electrically, electrons (like the air above) received by an electrically neutral body of material (tank) such as a man, a car, or an airplane, raise the voltage (pressure) at a rate depending upon the surface area and shape of the body. The voltage is determined by the surface characteristics (capacitance) of the body and the number of electrons on the surface. The larger the body the more electrons are needed to raise the voltage a specific amount. Hence the higher the capacitance of the body. Obviously a body that is large, like an aircraft, can receive and give up many electrons without a large change in voltage. Thus, it has a large capacitance. Likewise, a small body like a pin head can spare or take on considerably fewer electrons, but they will cause large changes in voltage, and hence it has a small capacitance. The main difference between the electrical charge and the air analogy is that with electricity the charge remains on the outside surface of the object while the air remains inside.

Capacitance is measured in terms of "farads." Actually, the farad is so large a quantity that it is more appropriate to talk about millionths of a farad or "microfarads" and millionths of 1/1,000,000 of a farad or "picofarads" (8). Using farads as the unit for capacitances associated with electrostatic systems would be like using light-years as a measure for a person's height. It could be done, but it would seem awkward.

Charge. Measured in coulombs or fractions thereof. The static charge on a body is measured by the number of separated electrons on the body (negative charge), or the number of separated electrons not on the body (positive charge). Electrons cannot be destroyed, so obviously when an electron is removed from one body it must go to another body. Thus, there are always equal and opposite charges produced [leaving behind a positive (+) void, called a "hole"]. Since it would be awkward to say that there are 6,240,000,000,000,000,000 electrons on a body we say instead that the body has a charge of one coulomb. A coulomb is simply a name for this specific quantity of electrons. In a more convenient form, 1 coulomb = 6.24 X 10^{18} electrons. In electrostatics a much more practical unit is the microcoulomb, representing a charge of 6.24 X 10^{12} electrons (8).

Charge Relaxation. The conductivity of a liquid determines the time taken for a charge to dissipate to ground. When the liquid is in a grounded, conductive container, the relaxation time "τ" (time for the charge to fall to 1/e or 37 percent of the original charge) is given by:

$$\tau = \frac{\epsilon_r \epsilon_o}{\gamma} \times 10^{12} \ \textit{seconds}$$

where τ = relaxation time (s)
ϵ_r = relative permittivity or dielectric constant of the liquid
ϵ_o = permittivity of free space
(8.85 X 10^{-12} farads per meter, F/m)
γ = conductivity of liquid in picosiemens per meter, (pS/m)

The electrical conductance of a conductor is measured in the unit of siemens, which is equal to one ampere per volt. Conductivity has units of conductance per unit length and appears in the older literature with the units mhos/cm.

The lower the conductivity, the longer the relaxation time and the greater is the ability of the liquid to hold the charge. If the charge is to fall to 5 percent of its original value, about three relaxation times are required and five relaxation times will reduce this to less than 1 percent of the original value. This derives from the relation:

$$Q = Q_o \exp(-t/\tau)$$

where Q = charge at time "t"
Q_o = original charge

Example: Assuming a liquid with relative permittivity of 2 and conductivity of 50 pS/m, the relaxation time is 0.35 s. The fraction of charge remaining after one second is given by

$$\frac{Q}{Q_o} = \exp\frac{-1}{0.35} = 0.06$$

Since the charge has fallen to about 6 percent of its original value in about 1 second, a value of conductivity of 50 pS/m or more is usually sufficient to prevent hazardous charge accumulation in grounded equipment. A liquid with conductivity of about 100 pS/m may be termed "high conductivity" for most purposes (8).

Current. Measured in amperes or fractions thereof. Just as waterflow is measured in terms of the amount of water that passes a certain point in a specific period of time (liters per minute), so too is the flow of electrons measured by time. The flow is called current. The current is measured in terms of electrons per second, but since this number would be tremendously large, it is more convenient to measure current in terms of "coulombs per second." It was difficult to keep saying "coulombs per second" so the word "ampere" was developed instead. Thus "15 coulombs per second" became "15 amperes" (8).

Dielectric. A dielectric is a material which has a conductivity low in comparison with that of a metal. It is characterized by its dielectric constant and dielectric loss, both of which are functions of frequency and temperature. The dielectric constant, ϵ_r, is a unitless number and may be defined and measured as the ratio of the capacitance, C, of an electric capacitor filled with the dielectric to the capacitance, C_0, of the same capacitor evacuated.

$$\epsilon_r = \frac{C}{C_0} = \frac{\epsilon}{\epsilon_0}$$

The capacitance of a capacitor of given dimensions is larger when there is a dielectric material between the plates than when the plates are only separated by air or vacuum. The relative permittivity or dielectric constant is the ratio ϵ/ϵ_0, where ϵ_0 is the permittivity of free space equal to 8.854×10^{-12} Farads/meter. Any dielectric material, when subjected to a sufficiently strong electric field, can provide conductive pathways, a phenomenon known as dielectric breakdown. The maximum electric field a material can withstand without the occurrence of breakdown is called the dielectric strength.

Energy. Measured in joules or millijoules. A spark is the result of energy being expended. Energy is required to do work. The measure of energy takes several forms. Often, if it is mechanical energy, it is measured in Newton-meters (joules), or foot-pounds; if it is thermal energy, it is measured in watt-seconds (joules), calories or British Thermal Units (BTUs). The energy of static sparks is usually measured in thousandths of a joule, which is a millijoule. A static spark must contain a certain minimum amount of energy to serve as an ignition source (8).

Incendive. A spark that has enough energy to ignite a combustible mixture is said to be incendive. Thus an incendive spark can ignite an ignitable mixture and cause a fire or explosion. A nonincendive spark does not possess the energy required to cause ignition even if it occurs within an ignitable mixture (8).

Incendivity. The ability of a spark to ignite an ignitable mixture.

Potential difference. Measured in volts, kilovolts or millivolts. If an electric charge *q* is placed in an electric field *E*, measured in volts per meter, then a force *qE* is exerted on the charge by the field. This means the charge has a potential energy by virtue of its position in the field. The change in potential energy of the charge in moving from one point *a* in the field to another point *b* is simply the mechanical work required to move it from *a* to *b* against the force due to the field. The electric potential difference, V, between points *a* and *b*, is equal to the work, W, divided by the charge *q*. The units of potential difference are work per unit charge, such as newton-meters per coulomb or joules per coulomb, which are both equivalent to a volt. It is incorrect to speak of the potential of one point without reference to another point. The point *b* is said to be at a higher potential than point *a* if work is done against electric forces when a positive charge is moved from *a* to *b*.

Potential differences or voltages are measured from a base or reference point. This point can be any voltage but is usually ground that is taken to be zero voltage. When one point with a potential of "x" volts to ground is compared with another point with a potential of "y" volts to ground, then we say that a potential difference of "x-y" volts exists between the two points. Obviously, then, when a point with a potential of 2500 (+) volts to ground is compared with a point with a potential of 1500 (-) volts to ground, the potential difference is 4000 volts.

Resistance. Measured in ohms or megohms. An electrical current encounters difficulty in passing through an electrical circuit or conductor. This difficulty can be measured and is called resistance. In hydraulics, the resistance to water passing through a pipe is called friction loss and is measured as a "head" or a pressure loss, lost over the length of the pipe. In electricity, resistance can be measured in terms of voltage drop over a part of the circuit, but is usually measured in terms of "ohms." The resistance of a circuit in ohms is equal to the ratio of a potential in volts to current in amperes

$$e.g.,\quad \frac{10V}{1A} - 10\,ohms, \quad \frac{1V}{1\mu A} - 1\,megohm$$

Work Function. Ordinarily electrons in a substance are prevented from escaping from the surface by a potential barrier. When an electron starts to move away from the surface it induces a corresponding positive charge in the material, which tends to pull it back into the surface. To escape, the electron must somehow acquire enough energy to surmount this energy barrier; the minimum energy needed to escape is called the work function, and varies from one material to another. Typical work functions are of the order of a few electron-volts (eV), where an eV is the unit of energy defined as the work of moving a charge of one electron through a potential difference of one volt, ($1\text{eV} = 1.6022 \times 10^{-19}$ J).

Electrostatic Generation and Accumulation

When two bodies of dissimilar materials are in close physical contact, there is a natural tendency for free electrons to move across the interface from one surface to the other. The electron transfer occurs as a result of a difference in work functions of the two materials. One surface gains electrons and becomes negatively charged, while the other having lost electrons becomes equally but positively charged. The surface which is positively charged is considered to have electron vacancies or "holes." Actually, these "holes" are associated with surface atoms or molecules which have lost one or more electrons and have become positively charged ions. In solids, the holes appear to move over the surface as a result of electrons moving to fill vacancies and creating vacancies elsewhere. It is really all electron flow.

There exists then an attractive force between the two surfaces. Although the distance between the two charged surfaces is very small, an electric field and difference in potential also exists. This double layer potential is called the "contact" or "zeta" potential and has a potential difference of only about 0.01 to 0.1 volt (6).

When the bodies are separated, work must be done in opposition to the attractive force. If the two materials in contact are good conductors of electricity, their separation results in excess electrons in the negatively charged material returning to the positively charged material before final contact is broken. If one or both of the materials is an insulator (nonconductor), the movement of electrons is impeded and with a rapid enough separation, some of the excess electrons will be trapped on one of the surfaces. The number of electrons which return is determined mainly by the conductivity of the surfaces and the speed of separation. The lower the conductivity and the faster the separation, the fewer is the number of electrons returned and the greater will be the surface charges on the separated materials. If one of the materials is a grounded conductor, it will not retain its charge.

The energy expended in separating the surfaces produces an increase in electrical potential or voltage between the surfaces. If the bodies are insulated from their surroundings and the electron donating surface does not receive an equal number of electrons to that originally lost, then upon separation it remains positively charged and the other surface remains negatively charged. If a conductive path is available between the now separated charged bodies, electron transfer will again occur and the charges on the bodies will be neutralized. If no such path is available, as is the case with insulators, the potential increase with separation may easily reach values of several thousand volts.

Initially, the two materials in direct contact could not be any closer than the nominal distance between atoms or molecules, which is about 10^{-8} cm, at which time the potential difference would be, let us say, 0.01 volt. If the two materials are then separated perfectly, that is without the flow of any electrons across the interface, the potential difference would increase inversely as the distance between the surfaces. When the surfaces are separated by 1 cm, the potential difference would be theoretically, one million volts!

In reality, the potential difference is much less, as there are no perfect insulators and some electrons do flow back through surface contacts. Also, the intense electric field which is produced ionizes the atmospheric gases between the separating surfaces and allows for charge dissipation through sparking or a visible glow termed a corona discharge. There is therefore an upper limit to the amount of accumulation which can occur because of corona discharge. In dry air at one atmosphere pressure, a charge density on a flat surface of 2.65×10^{-5} coulombs per square meter (C/m^2) or a voltage gradient of 30,000 volts per centimeter (V/cm), is the breakdown voltage (dielectric breakdown) for air, inducing ionization, resulting in a corona discharge. The residual charge on one or both of the materials, however, may still be the source of an incendive spark.

Often one of the objects will have a deliberate or inherently conductive path to the earth, and its charge is dissipated to the earth, which is considered to have an infinite capacity to absorb or release electrons. The other object, insulated from its surroundings, retains its charge and has an electric potential with respect to the surroundings. Theoretically, it could hold this charge indefinitely (e.g., in vacuum), but because no support holding the object, including air, is a perfect electrical insulator, its charge would slowly dissipate. Nature abhors a vacuum and charged bodies!

If an object is electrically nonconductive (an insulator), the movement or flow of electrons across its surface is restricted or even inhibited, and any charge on that surface tends to remain at the points where the electron transfer originally occurred. A highly charged insulating surface can be discharged with an attendant spark by bringing a grounded conductor close to the surface. Because electron movement on the nonconductor is impeded, only a limited area of the insulating surface will be discharged. This is true, whether the nonconducting surface is positively charged or negatively charged. The sparks produced by the discharge of such limited areas usually have too little energy to be a source of ignition. Therefore, nonconductors, the materials most often directly involved in electrostatic charge generation and accumulation are not usually the source of an incendive spark. However, charges on nonconductors can be the agent for build up or accumulation of charge on a conductor, which can then release all of its stored energy as an incendive spark.

On a conductive body, the charge is free to move about the surface. That is there exists no impediment to electron or "hole" migration. Because like charges repel each other and unlike charges attract, a negatively charged electron repels other electrons, a positively charged hole repels other holes, and an electron is attracted to a hole. The repulsive forces associated with the interacting electric fields of all of the excess electrons on a charged conductor cause the electrons to be distributed over the entire surface of the conductor. If no other body is in close proximity to a negatively charged conductive sphere, the excess electrons will be distributed evenly over the surface. For non-spherical bodies, the excess electrons will concentrate at those parts of the surface which have the least radius of curvature, such as edges, points, and bumps.

The electric field associated with a nonconductor charged body can have a strong influence on nearby objects. If the nearby object is an insulated conductor it will experience a separation of charges by induction. The repelled charge on the insulated conductor will reside as far away from the initial charged body as possible, and be free to release or receive electrons as the case may be. If another conductor, insulated or grounded, is brought close to the insulated conductor, a charge transfer may result in the form of an energetic, possibly incendive, spark. When the charged body which initially induced the separation of charges in the insulated conductor is removed, a reversed sequence of events will take place, which may also result in sparks. Induced charges in conductors can be more dangerous than the nonconductor charges on which they are dependent.

Materials handling processes which move nonconductive materials about, generally cause charge accumulations and the possibility of inadvertent discharges which may lead to the ignition of flammable substances. Charge generation and accumulation can occur in operations which are common in fireworks manufacturing. Some of the these operations are listed in Table ().

Electrostatic Dissipation

When charges are accumulated on dielectric materials, the charge usually resides on or near the surface, at least initially. It is possible to have a charge reside within the bulk of the material as is often the case in freshly pumped nonconductive liquids. It is generally easier to draw off a charge from a surface than from within the body of a dielectric material.

Two conductive bodies separated by a dielectric constitute a capacitor or condenser and when a potential difference is applied between the two conductors, a charge, can be stored. One of the conductors receives excess electrons and becomes negatively charged, while the other assumes the equal but positive charge. In many cases, when electrostatic charges are accumulated, one of the "conductors" is the earth and the insulating medium, the dielectric, is air. When a conductive pathway, more conductive at least than the air, is made available, the stored energy of the charged conductor is released, or it can be said, the capacitor is discharged, possibly producing a spark.

The energy stored in the capacitor is related to the capacitance, C, of the capacitor and the voltage, V, by the following equation:

$$Energy = \frac{C}{2} x V^2$$

The energy is determined in units of millijoules (mJ) when the capacitance is in picofarads, the potential difference is in volts and the product of $CV^2/2$ is multiplied by 10^{-9}.

It is the amount of energy in an electrostatic spark which determines whether or not it is incendive, not the voltage or the total charge on the source body. If a charged conductor releases its stored energy as a spark, the energy of the spark will always be less than the initial energy stored. This is because, energy will be expended heating the surface of the conductor at the point of discharge and effecting the dielectric breakdown of the surrounding insulator, e.g. air.

Experiments in air at atmospheric pressure with plane parallel (flat) electrodes have shown that a spark can occur between the electrodes separated by a distance of 0.01 mm when the dielectric breakdown voltage is minimally about 350 V. Increased gaps require proportionately higher voltages. Spark gaps less than about 0.5 mm precludes ignition of flammable gas/vapor air mixtures, because of flame quenching effects.

At the most favorable fuel to air ratios, determined experimentally, flammable mixtures of saturated hydrocarbon gases (e.g., methane, propane, n-hexane) and vapors in air require 0.2 to 0.3 mJ of spark energy to produce ignition. If the gases and vapors are mixed with oxygen, the minimum ignition energy (MIE) will likely be less than 0.01 mJ. An average MIE of 0.25 mJ for flammable gas or vapor mixtures with air is often cited as a good working value for assessing electrostatic hazards. For agricultural, carbonaceous, chemical, plastic and metal combustible dusts in air, MIEs range from as low as 10 mJ to greater than 1 joule (1,000 mJ), with 100 mJ being considered a fair representative value. However, for assessment of hazards, the minimum ignition energies at ambient temperatures and pressures should be considered to be 0.1 mJ for vapors in air, 1 mJ for mists in air and 10 mJ for non-energetic material dusts in air.

McIntyre (12) has reported MIEs for dusts of many military pyrotechnic compositions, which were measured in a conventional Hartmann Apparatus. Values for the minimum ignition energies were as low as 2.8 mJ for a Stab Mixture containing lead azide and lead styphnate to greater than 50 J for several white flare mixtures, containing sodium nitrate, magnesium and the alkyd resin, Laminac. Interestingly, a flash and sound mixture containing just potassium perchlorate and aluminum had a MIE of 5 mJ, whereas another containing potassium perchlorate, aluminum, antimony sulfide and sulfur (M-80 Detonation Simulator mixture) had a MIE of 1.25 mJ. The lower MIE for the sulfur/sulfide containing mixture is at least consistent with the understanding that the presence of sulfur or sulfides in pyrotechnic compositions tend to increase ignitability.

An important consideration in assessing electrostatic hazards in a process is that of relaxation time. Just as there is no perfect conductor, there is no perfect insulator. If a charge is generated and accumulated on a nonconductor or an insulated conductor, sooner or later, it will be dissipated to the environment or it is said the charge is relaxed. The more conductive a nonconductor is, the more rapid the dissipation occurs, or the shorter is the relaxation time.

Electrostatic charge accumulation is a dynamic process. A charge accumulates on a body when the rate of generation exceeds the rate of dissipation. Because the rate of dissipation will be controlled by the electrical properties of the materials involved in a process, which often cannot be significantly altered, the best approach to minimizing charge accumulation is to reduce the rate of generation. Reducing the rate of generation means doing operations **slowly**. This may be accomplished by reducing the flow rate of a nonconductive fluid through a pipe, the rotation rate of a mixer or the feed rate of a powder through a sieve. When working with energetic materials and addressing electrostatic ignitions problems, a basic tenant of safe operations is "whenever possible, do things slowly."

ELECTROSTATIC CALCULATIONS

A set of everyday situations creating possible electrostatic ignition hazards is presented in this section. Each situation is described with enough factual information to do one or more calculations to better understand the associated hazards.

Accepted electrostatic data and other electrical and mechanical properties of materials, for the calculations, are, in part, provided in the numbered paragraphs and tables which follow. Much of this information was taken from the excellent papers by Schmieg (3), Mancini (4), and Eichel (6).

Accepted Electrostatic Values (6)

1. The zeta or contact potential, ζ, is usually of the order of 0.01 to 0.1 volt.

2. About 14,000 volts is needed to produce a spark between needle points 1.3 cm (0.5 inches) apart. Over 20,000 volts is needed between spheres. Some authorities consider it necessary to have an electric field strength of 30,000 volts/cm before sparking can occur.

3. About 350 volts is needed for a spark to jump plates 0.01 mm apart. This is considered to be the minimum sparking potential.

4. The maximum charge density possible in air is 2.65×10^{-9} coulombs/cm^2 of surface. Above this value, corona discharge occurs.

5. Hydrogen in air has been ignited electrostatically with as little as 0.02 mJ at 1,300 volts. Hydrogen explosions can be initiated by a corona discharge or by St. Elmo's fire.

6. The required spark energy for an explosion is dependent upon the combustible material's explosive limits. The lower and upper explosive limits for flammable vapors in air are respectively, about 50% and 400% of the stoichiometric proportion for complete combustion. At the high and low limits, 5 to 10 mJ of spark energy is needed for ignition. At near stoichiometric proportions, the spark energy required for ignition is about 0.2 mJ.

7. Some electrostatic voltages commonly encountered are:
   (a) Man walking on dry carpet, or sliding across an automobile seat, etc. -- up to 5000 volts in dry weather;
   (b) Truck or automobile traveling over pavement in dry weather -- up to about 10,000 volts;
   (c) Belts running over pulleys -- up to 30,000 volts, 20,000 - 25,000 volts is common;
   (d) Person removing a nylon jacket in dry weather -- up to 10,000 volts.

Table 1. Capacitance of Various Objects (4).

Object	Capacitance (picofarads)
Small scoop, beercan, tools	5
Buckets, small drums	20-50
50-100 gallon containers	100
Person	100-400
Automobile	500
Tank Truck	1000

Table 2. Charge buildup for various operations (4).

Process	Charge (coulombs/kg)
Sieving	10^{-9} to 10^{-11}
Pouring	10^{-7} to 10^{-9}
Grinding	10^{-6} to 10^{-7}
Micronizing	10^{-4} to 10^{-7}
Sliding down on incline	10^{-5} to 10^{-7}
Pneumatic transport of solids	10^{-5} to 10^{-7}

Table 3. Static Charge Densities for Various Operations as Percentages of Theoretical Maximum of 2.65×10^{-9} coulombs/cm^2 (4).

Process	Percentage
Sliding contact	Up to ~ 8%
Rolling contact	Up to ~ 8%
Dispersion of dusts	1-10 %
Pneumatic transport of solids	Up to ~ 60%
Sheets pressed together	Up to ~ 60%
Close Machining	Up to 100%

Table 4. Ignition Energies for Select Dust Clouds (3).

Dust	Minimum Ignition Energy (mJ)
Aluminum	50-280
Blackpowder	320
Bone glue	140
Chocolate crumbs	100
Cork dust	35-45
Soap powder	60-960
Wood dust	20-40

Table 5. Electrical Properties of Select Fluids

Substance	Volume Resistivity, (Ωm)	Dielectric Constant, (ϵ_r)	Ref.
Air		1.0	15
acetone	1.3×10^4	20.7	13
2-butanone (methyl ethyl ketone)		18.5	15
dichloromethane (methylene chloride)	1.9×10^4	9.08	16,15
methanol	2.3×10^4	32.6	13
toluene	$> 1 \times 10^{12}$	2.39	13
water	$10^2 - 10^5$	80.37	15

Conductivity = 1/resistivity = 1/ohm-meter (1/Ω-m) = siemens/meter (S/m). Measurements were taken at or near 25°C. The resistivity of organic liquids is greatly affected by traces of impurities.

Table 6. Electrical Properties of Select Solids

Substance	Volume Resistivity, (Ωm)	Dielectric Constant, (ϵ_r)	Ref.
d-cocaine		3.1	15
Gilsonite		2.7	13
Glasses			
Borosilicate (Pyrex 7740)	10^{13}	5.0	3
Plate	2×10^{11}	7.5	13
Nitrocellulose	$1\text{-}1.5 \times 10^{9}$	6.4, 8.4	14,15
Paper, dry	$\sim 10^{10}$	1.7	13
Paper, kraft		2.9	13
Paper, dry pressboard, d=0.8		3.2	13
Paraffin	10^{13} - 10^{17}	2.2	13
Plastics			
Acrylic (Lucite, Perspex)	$>10^{13}$	3.4	13
Nylon	4×10^{12}	3.5	13
Polycarbonates (Lexan)		3.2	13
Polyethylene, high density	10^{14} - 10^{15}	2.3	13
Polypropylene	10^{13} - 10^{15}	2.2	13
Polystyrene, general purpose	10^{15} - 10^{19}	2.6	13
Polyurethane	10^{9} - 10^{12}		13
Rubber, chlorinated	1.5×10^{11}	3	14
Shellac	10^{7}		14
Sulfur	10^{14} - 10^{15}	3.8-4.4	13
Wood, dry	10^{8} - 10^{11}	3.0	1

Conductivity = 1/resistivity = 1/ohm-meter (1/Ωm) = siemens/meter (S/m).
Measurements were taken at or near 25°C.

The persons and events presented and discussed in these examples are contrived, for illustration purposes only, and any similarity with real persons or events is coincidental.

Example 1

A woman, wearing non-conductive shoes, removes a wool sweater in a room with less than 50% relative humidity. A triboelectric charge on her body is then dissipated through grounding with a spark at a light switch. Could this spark have ignited a natural gas leak?

Solution:

Using an approximate value of 300 picofarads (pF) for the capacitance of a human body and the value of 10,000 volts associated with the removal of a garment, one can determine the maximum potential energy in the charged person:

$$\begin{aligned} E &= \frac{1}{2}CV^2 \\ &= \frac{1}{2}(300\times 10^{-12}F)\,(1\times 10^{4}\,V)^2 \\ &= 1.5\times 10^{-2}\,J \\ &= 15\,mJ \end{aligned}$$

Considering a natural gas (mostly methane) and air mixture has a MIE of about 0.30 mJ, the spark could easily have been incendive. The mere presence of natural gas would not necessarily have resulted in ignition and perhaps a natural gas explosion. The natural gas would need to be present at a concentration in air which was between the upper and lower flammability limits. Also, within the limits, the concentration would still need to be one which could be ignited by a 15 mJ electrostatic discharge.

The 15 mJ spark is also below the minimum energy required to ignite ordinary dust clouds, as can be seen in Table 4. However, this energy is certainly sufficient to ignite dust layers and the dust clouds of several pyrotechnic mixtures.

An assumption made for the calculation was that the charge on the person was completely lost at the grounded light switch. This would only be true if the person was a good electrical conductor, Human bodies are, from an electrostatics standpoint, good conductors, just like a piece of copper wire. In fact, we are considered "leather bags filled with water" (17).

Example 2

Estimate the charge buildup, accumulated energy and the accumulated voltage as a result of a man transferring 15 kg (33 lbs) of sulfur, using a metal scoop, into a 100 liter polypropylene drum. Assume the man's capacitance is 300 pF, he is wearing non-conductive shoes, he is 178 cm (70 inches) tall, weighs 75 kg (165 lbs) and the relative humidity is below 50%.

Solution:

This operation involves a sliding contact process. From Table 3, the operation would produce a maximum charge density of 8% of 2.654 X 10^{-9} coulombs/cm^2 or 2.1 X 10^{-10} coulombs/cm^2. Equal and opposite charges accumulate on the man's body and the sulfur. The magnitude of the charge on the man's body is based upon his surface area. From reference (18), the surface area of a man 178 cm tall and mass of 75 kg, is 1.92 m^2, which equals 1.92 X 10^4 cm^2. Therefore the charge buildup is

$$Q = (2.1\times10^{-10}\,\frac{coulombs}{cm^2})\,(1.92\times10^4 cm^2) = 4.0\times10^{-6}\,coulombs\ .$$

The accumulated energy is given by

$$J = \frac{Q^2}{2C} = \frac{(4.0\times10^{-6}\,coulombs)^2}{2(300\times10^{-12}\,farad)} = 2.7\times10^{-12}\,Joules = 27\,mJ\ ,$$

and the accumulated voltage is

$$V = \frac{Q}{C} = \frac{4.0\times10^{-6}\,coulombs}{3.0\times10^{-10}\,farad} = 13{,}000\ Volts\ .$$

These results show the energy and voltage exceeding the requirements for generating an incendive spark. The spark could be produced if the man approached a ground with a hand or with the scoop. The charge on the sulfur in the insulated, polypropylene drum represents another potential ignition source. For example, if a grounded object was placed close to the sulfur, an energetic spark could be produced. Because sulfur is a non-conductor, however, the energy of any single discharge would be expected to be much less than 27 mJ.

Example 3

If the charged sulfur, in example 2, is assumed to behave as a liquid and is contained within a grounded, conductive vessel, what would be the charge relaxation time and what charge would remain in the sulfur 24 hours after the charging?

Solution:

From Table 6, the volume resistivity and the dielectric constant for sulfur are respectively 10^{14} - 10^{15} Ωm and 3.8 - 4.4. For this calculation the values of 10^{15} Ωm and 4.0 are used. The conductivity, γ, is then $1/(10^{15}\Omega m) = 10^{-15}$ S/m. The relaxation time is then determined as

$$\tau = \frac{\epsilon_r \epsilon_o}{\gamma} = \frac{(4.0)(8.85\times10^{-12}\,F/m)}{10^{-15}\,S/m}$$
$$\tau = 3.5\times10^{4}\,seconds \approx 10\,hours\ .$$

The initial charge in the sulfur is also 4.0 x 10^{-6} coulombs. The charge remaining after 24 hours is given by,

$$\begin{aligned} Q &= Q_o \exp\left(\frac{-t}{\tau}\right) \\ &= (4.0\times10^{-6} coulombs)\exp\left(\frac{-24}{10}\right) \\ &= 3.6\times10^{-7}\,coulombs \end{aligned}$$

or the percentage of the initial charge remaining is,

$$\frac{3.6\times10^{-7}\,coulombs}{4.0\times10^{-6}\,coulombs}\times10^{2} = 9\%$$

Because the sulfur is not a liquid at room temperature, and does not have the attendant mobility, the charge would be dissipate at even a slower rate.

Example 4

A pyrotechnician holds steady with one hand a metal sieve while forcing 5 kg (11 lbs.) of potassium perchlorate through the sieve with his other hand. The sieve rests atop a polyethylene tray into which the $KClO_4$ falls. Neither the worker, nor the sieve is grounded. If the capacitance of the worker is 200 pF, estimate the charge, energy and voltage accumulations.

Solution:

From Table 2, a sieving process results in charge accumulation of 10^{-9} to 10^{-11} coulombs/kg of solids sieved. Using the larger value of 10^{-9} coulombs/kg, the charge accumulation is,

$$Q = (1\times10^{-9}\,coulombs/kg)(5\,kg) = 5\times10^{-9}\,coulombs$$

r this situation, the worker and the sieve are considered a set of capacitors in parallel. The capacitance of the two is equal to the sum of the individual capacitances. The sieve is about the size of a small bucket, so from Table 1, its capacitance is estimated as 20 pF. Therefore, the capacitance of the worker-sieve combination is 220 pF. The accumulated energy is then,

$$J = \frac{Q^2}{2C} = \frac{(5\times10^{-9}\,coulombs)^2}{2(220\times10^{-12}\,F)} = 6\times10^{-8}\,J = 6\times10^{-5}\,mJ$$

The accumulated voltage is,

$$V = \frac{Q}{C} = \frac{5\times10^{-9}\,coulombs}{220\times10^{-12}\,farads} = 23\;volts$$

These results suggest that sieving of modest quantities of pure compounds such as potassium perchlorate represents no significant electrostatic hazard. But, this is not correct. Actually, the sieving process described above involves the crushing and rubbing of potassium perchlorate on the meshed surface of the sieve. These operations increase the charging considerably and result in energy accumulations which could lead to incendive spark generation. The sieve and the worker should be grounded.

The last example of electrostatic calculations is considerably more complex than the previous examples. The solution relies upon some fundamental principles and associated equations taken from several disciplines including electrostatics and combustion science.

This example concerns a charging mechanism known as a streaming current. A streaming current, I_s, is developed as a result of fluid flow through a conduit,such as a pipe, hose, trough, etc. A streaming current (ampere), produced for any period of time (seconds), results in charge generation (ampere-seconds = coulombs).

When a fluid flows through a pipe, there is an uneven distribution of electrons at the wall-fluid interface. A charged layer of fluid at the wall develops a voltage gradient. This layer is called an electrical double layer, and is equivalent to the fluid dynamical concept of a boundary layer.

For a rigorous treatment of the concept of the electrical double layer, the reader is referred to the book by Adamson (19), and the reference contained therein.

For the purposes of this example calculation, the electrical double layer can be thought of as a very thin region of relatively slow moving fluid in contact with the inner surface of a pipe, hose, etc. And at this layer, fluid particles from the mainstream can become charged as a result of a gain or loss of electrons from and to the surface. If the flow of fluid through the pipe is such that at any point in the flow, fluid particles (small molar masses) are swirling, moving in very irregular paths, the flow is said to be turbulent. If the fluid particles move along smooth paths, parallel with the overall direction of flow, in laminas, or layers, with one layer gliding smoothly over an adjacent layer, the flow is said to be laminar.

Turbulent flow affords the opportunity for more fluid particles from the bulk flow to reach the electrical double layer and become charged, than does laminar flow. For this reason, turbulent flows generally produce higher streaming currents.

Whether a flow is laminar or turbulent or in transition is distinguished by the flow's Reynolds number. The Reynolds number is dimensionless, that is, it has no units. A Reynolds number of about 2,000 or less is considered indicative of laminar flow; one in the range of 2000 to 4000 is transitional flow and a value greater than 4000 indicates turbulent flow.

The Reynolds number is such an important parameter for analyzing non-compressible fluid flow (i.e., liquids) that discussions of its origins and applications can be found in any introductory textbook on fluid mechanics.

Example 5

On a cold fall day, a worker at a fireworks plant transferred 19 liters (5 gals) of dichloromethane (methylene chloride) from an upright 208 liter (55 gal) drum into a 19 liter (5 gal) safety can. She used a hand pump placed in the drum. The hand pump was constructed of polyethylene, including the delivery hose which directed the solvent flow into a polyethylene funnel; the funnel was placed in the can. She pumped the solvent at a rate of 26.5 liters/minute (7 gals/min).

The drum and can were not electrically bonded and both containers were resting on non-conductive flooring. The woman was wearing non-conductive shoes and because the solvent storage room was not heated, she was also wearing gloves. She did not remove the gloves at any time while in the solvent room.

Because the filled can was quite heavy, nearly 27 kg (57 lbs), the worker lifted the can onto a wooden dolly, which was fitted with hard rubber wheels and a push bar. She then wheeled the dolly down a short hallway to the entrance of another storage room in which powdered metals were stored. She needed to pick up a few kilograms of a powdered magnalium.

A metal door to the room was closed. She removed the glove on her right hand in order to manipulate the door latch. Upon touching the latch, she received a static shock. She opened the door and a moment later there was an explosion, which blew out walls and the sheet metal roof off the storage room and sent the woman flying. Miraculously, she survived to tell her story. An explosion investigation revealed several additional facts:

1. The woman was a non-smoker.
2. She was wearing clean cotton coveralls.
3. The metals storage room interior dimensions were 1.83 m (6 ft) X 2.44 m (8 ft) and 2.44 m high.
4. The metals storage room had no electrical service.

5. The nearest electrical fixture to the entrance of the metals storage room was an explosion proof light.

6. There was a drum containing approximately 100 kg (220 lbs) of powdered magnesium in the metals storage room. The lid to this drum was off and the powdered magnesium had become dampened as a result of a leaking sky light directly above the drum.

7. In addition to the open drum of powdered magnesium, there were several other closed drums of different powdered metals. Altogether, the drums containing powdered metals occupied about 40% of the room's volume.

8. With the door closed, the metals storage room had no ventilation, except perhaps for the small hole in the roof, and some leakage around the door.

9. Prior to the explosion, no one had been in the metals storage room for nearly three weeks. During that period, it had rained heavily twice.

10. When opened, the door to the metals storage room did swing out far enough to make contact with the solvent safety can on the dolly.

11. In the solvent storage room, no attempt was made to ground the methylene chloride drum or bond to it the safety can because the solvent was considered to be non-flammable. (Note: while dichloromethane vapors can be ignited at 556°C and the upper and lower flammable limits in air are 14% and 22% respectively, the solvent is considered non-combustible in normal use.)

12. The relative humidity in both storage areas was less than 50%, the temperature was 1°C, and the pressure was one atmosphere (1.01×10^5 Pa).

The investigators concluded that the explosion was caused by an electrostatic ignition of a hydrogen-air mixture in the metals storage room. The hydrogen was produced by the reaction of water with the powdered magnesium.

Are these conclusions valid?

Solution:

If the source of ignition was an incendive spark from an electrostatic discharge, the source was not the charge on the woman's body. That charge was dissipated at the door latch. Most likely, the incendive spark had its origins in the charge on the safety can, which was generated by a streaming current in the flow of the methylene chloride through the filler hose, the funnel, and finally, into the can.

The approach to the solution has several steps:

1. Calculate the Reynolds number for the methylene chloride flow.
2. Determine the charge relaxation time for methylene chloride.
3. Calculate the streaming current for the methylene chloride flow.
4. Estimate the accumulated charge buildup, energy and voltage on the can
5. Estimate the concentration of hydrogen in air which could be ignited by an incendive spark with energy equal to the accumulated energy on the can.
6. Determine if sufficient magnesium was available to react with water to produce the hydrogen concentration estimated in step 5.

Pertinent Data

For the methylene chloride:
Volume flow rate, $q = 26.5$ l/min $= 4.4 \times 10^2$ cm^3/s
relative permittivity, $\epsilon_r = 9.08$ (from Table 5)
Viscosity, μ(at 15°C) $= 4.5 \times 10^{-4}$ Pa·s $= 4.5 \times 10^{-3}$ (dynes·s)/cm^2
density, ρ(at 0°C) $= 1.36$ g/cm^3
Molecular diffusivity, $D_m \approx 2 \times 10^{-5}$ cm^2/s [Estimated from ref.(20)]
resistivity $= 1.9 \times 10^4$ Ωm (from Table 5)
Conductivity, $\gamma = 5.3 \times 10^{-5}$ S/m

Hose I.D. = 2.54 cm, Cross-sectional area = 5.1 cm^2
Capacitance of the safety can = 30 pF (from Table 1)
Volume of the metals storage room = 10.9 m^3

Several equations exist to calculate a streaming current. The choice of appropriate equation to use depends upon the flow conditions.

Step 1: The Reynolds number, R_e, is given by

$$R_e = \frac{d\,\bar{u}\rho}{\mu}$$

where d is the hose diameter; $\bar{u}$, the fluid velocity; ρ, the fluid density; and μ, the fluid viscosity.

Then with,

$$\bar{u} = \frac{q}{A} = \frac{4.4\times10^{2}\,cm^{3}/s}{5.1\,cm^{2}} = 86\,cm/s\ .$$

The Reynolds number is,

$$\begin{aligned}R_e &= \frac{(2.54\,cm)(86\,cm/s)(1.36\,g/cm^{3})}{(4.5\times10^{-3}\,\frac{dynes\cdot s}{cm^{2}})(1\,\frac{g}{dynes\cdot cm\cdot s})}\\ &= 6.6\times10^{4} \qquad \therefore \text{Turbulent Flow}\end{aligned}$$

Step 2: The relaxation time for methylene chloride is

$$\begin{aligned}\tau &= \frac{\epsilon_o \epsilon_r}{\gamma} = \frac{(8.85\times10^{-12}\,F/m)(9.08)}{5.3\times10^{-5}\,S/m}\\ &= 1.5\times10^{-6}\,seconds\ .\end{aligned}$$

With such a short relaxation time, any charge on the methylene chloride as it enters the safety can, would be immediately lost to the can.

Step 3: With turbulent flow, the streaming current, I_s, can be calculated with the following expression,

$$I_s = \left[\frac{(1.9\times10^{-15}A)}{(cm/s)(V)}\right]\frac{d\,\epsilon_r\,\zeta\,\bar{u}}{\delta}$$

where d is the hose diameter (cm), ζ is the zeta potential and δ is the double layer thickness (cm).

The double layer thickness, δ, is computed from

$$\begin{aligned}\delta &= \sqrt{D_m \tau} = \sqrt{(2\times10^{-5}\,cm^{2}/s)(1.5\times10^{-6}\,s)}\\ &= 5\times10^{-6}\,cm\ .\end{aligned}$$

The streaming current is then,

$$I_s = \left[\frac{1.9\times 10^{-15}A}{(cm/s)(V)}\right]\frac{(2.54\,cm)(9.08)(0.01\,V)(86\,cm/s)}{5\times 10^{-6}\,cm}$$
$$= 7.5\times 10^{-9}A\ .$$

Step 4:

The accumulated charge buildup on the safety can would equal the total charge carried into the can by the methylene chloride. Therefore,

$$Q = I_s t\ ,$$

where t is the duration of the flow in seconds, which equals the time it took to fill the safety can.

Therefore,

$$t = \frac{safety\ can\ volume}{volume\ flow\ rate} = \frac{19\ l}{26.5\ l/m}$$
$$= 0.7\ \text{min} = 42\ s\ .$$

Then,

$$Q = (7.5\times 10^{-9}\,A)(42\,s) = 3\times 10^{-7}\ coulombs\ .$$

The accumulated energy on the safety can is,

$$J = \frac{Q^2}{2C} = \frac{(3\times 10^{-7}\,coulombs)^2}{2(30\times 10^{-12}F)}$$
$$= 1.5\,mJ$$

and the accumulated voltage is

$$V = \frac{Q}{C} = \frac{3\times10^{-7} coulombs}{30\times10^{-12} F}$$
$$= 10{,}000 V .$$

The accumulated energy is more than adequate to provide an incendive spark for many flammable vapor-air mixtures. The voltage is high enough to provide a spark across a gap which far exceeds quenching distances, but is not so high as to cause charge dissipation into the air, by, for example, corona discharge.

Step 5:

An electrostatic spark energy of 1.5 mJ would equal or exceed the ignition energy for hydrogen-air mixtures in which the hydrogen volume percentage is between about 5 and 68% (20). The lower and upper flammability limits for hydrogen-air mixtures is 4 to 75% hydrogen, so a 1.5 mJ spark would be incendive for most of the flammability range. The Minimum Ignition Energy for hydrogen-air mixtures is 0.017 mJ and corresponds to a hydrogen volume percentage of 28% (20).

The largest quenching distance for the 5-68% hydrogen range is 0.4 cm. A 10,000 volt potential is capable of producing a spark of length greater than 0.4 cm. The charge on the safety can was therefore more than adequate to serve as an electrostatic ignition source for most hydrogen-air mixtures.

Step 6:

The volume of air in the metals storage room was 60% of the room's volume, or $0.6(10.9\ m^3) = 6.5\ m^3$.

The volume of hydrogen in the room required to provide the 5% concentration would be $0.05(6.5\ m^3) = 0.33\ m^3$ or 330 liters. To completely fill the room with hydrogen, displacing all the air, would, of course, require 6,500 liters. Because the room's temperature on the day of the explosion was so close to 0°C, the 330 and 6500 liter quantities will here be considered the volumes at standard temperature and pressure (STP).

Magnesium reacts with water according to the following equation,

$$Mg + 2\,H_2O = Mg(OH)_2 + H_2$$

Each 22.4 liters of hydrogen at STP will according to the balanced equation require the reaction of one gram-atom of magnesium, which equals 24.3 g. Therefore, to produce the minimum concentration of hydrogen, that is 5%, which can be ignited with a 1.5 mJ spark, (330 liters/22.4 liters) x 24.3 g = 360 g of magnesium would have had to react. This also would require that none of the hydrogen produced escaped the room. That is unlikely.

Considering the small, but nonetheless available ventilation in the room, and the diffusivity of hydrogen it is also possible that over a several day period, the room was nearly completely filled with hydrogen. To produce 6,500 liters of hydrogen at STP requires the reaction of 7 kg of magnesium. However, given the nature of gas displacement by another gas, several tens of kilograms of the magnesium would have had to react to produce enough hydrogen to achieve a nearly air free condition. A 100% hydrogen atmosphere, would not be ignitable.

If the room's free volume was nearly 100 % hydrogen, the door being opened by the woman could have created the opportunity for hydrogen to mix with air and form an explosive mixture. Both in the vicinity where the door grounded the charge on the safety can and to a limit extent within the room. Because the explosion damage was limited to the room, it probably did not contain a well mixed, stoichiometric mixture, at the time of ignition. Determining the actual concentration of hydrogen in the metals storage room would be very difficult, if not impossible.

An old adage in electrostatics goes "All accidental explosions are caused by a static spark.........until you find out what really happened." However, in this situation, the investigators' assessment appears to be valid.

CONTROL OF STATIC ELECTRICITY

There are several ways to eliminate or minimize the effects of undesirable or dangerous static charging. A static charge can be actively removed or allowed to naturally dissipate. In either case, it is desirable that the charge be dissipated safely. If one method is impractical for a particular situation, another may be considered. Using two or more methods for mitigating charge generation and accumulation usually produces good results and in terms of fireworks manufacturing safety, it is a prudent technique.

Control Methods

Humidification

If an area's **relative humidity** is maintained at a high level, many nonconductive materials commonly found in fireworks manufacturing facilities, will adsorb enough water from the air to become slightly conductive. This surface moisture may produce conductivities high enough to dissipate static charges as fast as they are generated. As was discussed earlier, when the dissipation rate equals or is greater than the generation rate, no charge accumulates. Cellulosics such as paper, cardboard and wood and cotton and even glass adsorb moisture readily. At relative humidities above about 65%, these materials become sufficiently electrostatically conductive, so that static charge accumulations are small or non-existent. Even at relative humidities near 50%, there is often significant attenuation of static charging.

Other materials, such as many plastics, do not adsorb moisture, even at conditions of extreme humidity (80-95%). Teflon and polystyrene are good examples of man made polymers which do not adsorb any significant amount of water so as to make the surfaces electrostatically conductive. They are good electrical insulators, even at high relative humidities. Polypropylene and polyethylene seem to be better conductors at comparable relative humidities. For extensive or long-term continuous control of humidity, explosion proof humidifiers in fireworks manufacturing areas may be required. For temporary relief from electrostatic problems, hanging wet rags in a low relative humidity area may be satisfactory.

It is usually stated that a relative humidity of greater than 50% will significantly reduce static charge accumulations on most common materials.

Bonding and Grounding

Where natural conditions, including humidity, fail to provide adequate charge dissipation rates, alternate conducting paths are appropriate. "Bonding" refers to connecting two or more conductive objects together by means of a conductor, such as a metal wire or strap. "Grounding" or "earthing" refers to connecting one or more conductive objects to the ground. Grounding is a special form of bonding, where the earth represents one of the bonded objects. Bonding minimizes potential differences between conductive objects.

Often grounding can be achieved with a connection to underground piping or large metal storage tanks resting directly on the ground. In fireworks manufacturing, it important to ground workers. This may be achieved through the use of conductive shoes or conductive leg or wrist straps. Schmieg (3) offers a note of caution for such cases: "Do not attach very low-resistance grounds to people. There is always danger of an electric shock by accidental contact with a source of 110 V AC. There must be no risk of high current through a person's body in these cases. Make sure that any ground connection involving people has a resistance greater than 25,000 Ω".

Bonding wires on equipment should have adequate capacity to carry the largest currents which may be anticipated for the installation or process. A No.10 AWG wire is a reasonable compromise between current carrying capacity, physical strength and cost (25). A ground wire or strap, which is intended to service power circuits or lightning protection systems, will certainly be more than adequate for electrostatic charge dissipation.

Ionization

Air can be made to be substantially more conductive either by ionizing air molecules directly or introducing ions into the air. Air which has become more conductive through ionization will promote dissipation of accumulated charges on bodies.

Open flames produce small concentrations of ions, as part of the combustion process. Such open flame ionizers would be for obvious reasons, inappropriate for fireworks manufacturing facilities.

Other ion generators directly ionize constituent air molecules by radioactive materials or high voltage AC or DC sources. In many cases, the high voltage ionizers also produce ozone from the oxygen in the air. Additional details on ionization equipment can be found in references (3,8 20,22,23).

Passive discharge

A static charge, on a conductive body which is not spherical, will, because of self-repulsion, concentrate on the surfaces having the least radius of curvature. A sharp needle point is a good example of a surface with a small radius of curvature. Charge concentration at a needlepoint can produce ionization of surrounding air, rendering the air conductive. For this reason, metal bars holding a line of needle points or wire brushes are fastened to equipment to mitigate static charge accumulation. Because of their shape, these devices are often called static combs. An advantage of static combs over other air ionizers, is that they require no power supply. Their major shortcomings are that they do not completely dissipate charges, leaving the equipment to which they are affixed still at possibly hazardous potentials and the sharp needles are a potential point (pun intended) of personal injury.

Direct Control of Conductivity

Materials, which are normally insulators can be made more conductive with minor changes in bulk composition or surface properties. These changes will only be made if they do not interfere with the other useful properties of the material. Examples of everyday materials which are modified to increase electrical conductivity are: fabrics into which metal fibers are woven, plastics and rubbers with carbon added, conductive sprays and paints applied to many surfaces, including carpets and floors.

Instruments for the Measurement of Static Electricity

Several instruments are available for the measurement of one or more electrical parameters of electrostatic interest. They include, electroscopes, electrostatic voltmeters, electrometers, field mills, portable electrostatic fieldmeters, and high resistance ohmmeters. The applicability and limitations of the devices are discussed in references (2,3,6,10,22,24,25).

Specific Recommendations for Electrostatic Control

The following recommendations are taken directly from references (8,24,25).

1. Use flexible conductors for bonds which are frequently connected and disconnected (25).

2. Use conductive V-belts on power equipment, [such as drum mixers for ball stars]. The belts should meet the requirements of the International Standards Organization specification 1813. Conductive belting should have a resistance to ground not exceeding 600,000 ohms (25).

3. All conductive parts of equipment should be grounded so that resistance does not exceed 25 ohms, unless 10 ohms is required for lightning protection (25). The resistance of conductive rubber should not exceed 250,000 ohms (24).

4. Conductive floors and conductive shoes should be used for grounding personnel at operations involving explosives having an electrostatic sensitivity of 100 mJ or less (25). [Personnel wearing conductive shoes on a conductive floor is always a good idea in fireworks manufacturing, regardless of the electrostatic sensitivity of the pyrotechnics processed.]

5. Humidification for preventing static charge accumulations and incendive discharges, is usually effective if the relative humidity is above 60%. However, certain materials such as metal powders and some pyrotechnic compositions cannot be exposed to air with 60% relative humidity because of the possibility of spontaneous ignition (25). [If this is the case for a fireworks composition, it would be good idea to use a different mixture!]

6. Although silk and some synthetic fibers are excellent insulators, and undergarments made from them exhibit static phenomena, there is no conclusive evidence to indicate that wearing such undergarments constitutes a hazard (8).

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